27 february 2012
Rencontres de La Thuile

Dark Matter searches: a theoretical perspective

Marco Cirelli
(CERN-TH & CNRS IPhT Saclay)

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Introduction

A matter of perspective:

Introduction

A matter of perspective:

SuSy DM

Non SuSy DM

Introduction

A matter of perspective:

SuSy DM

Non SuSy DM

?

Introduction

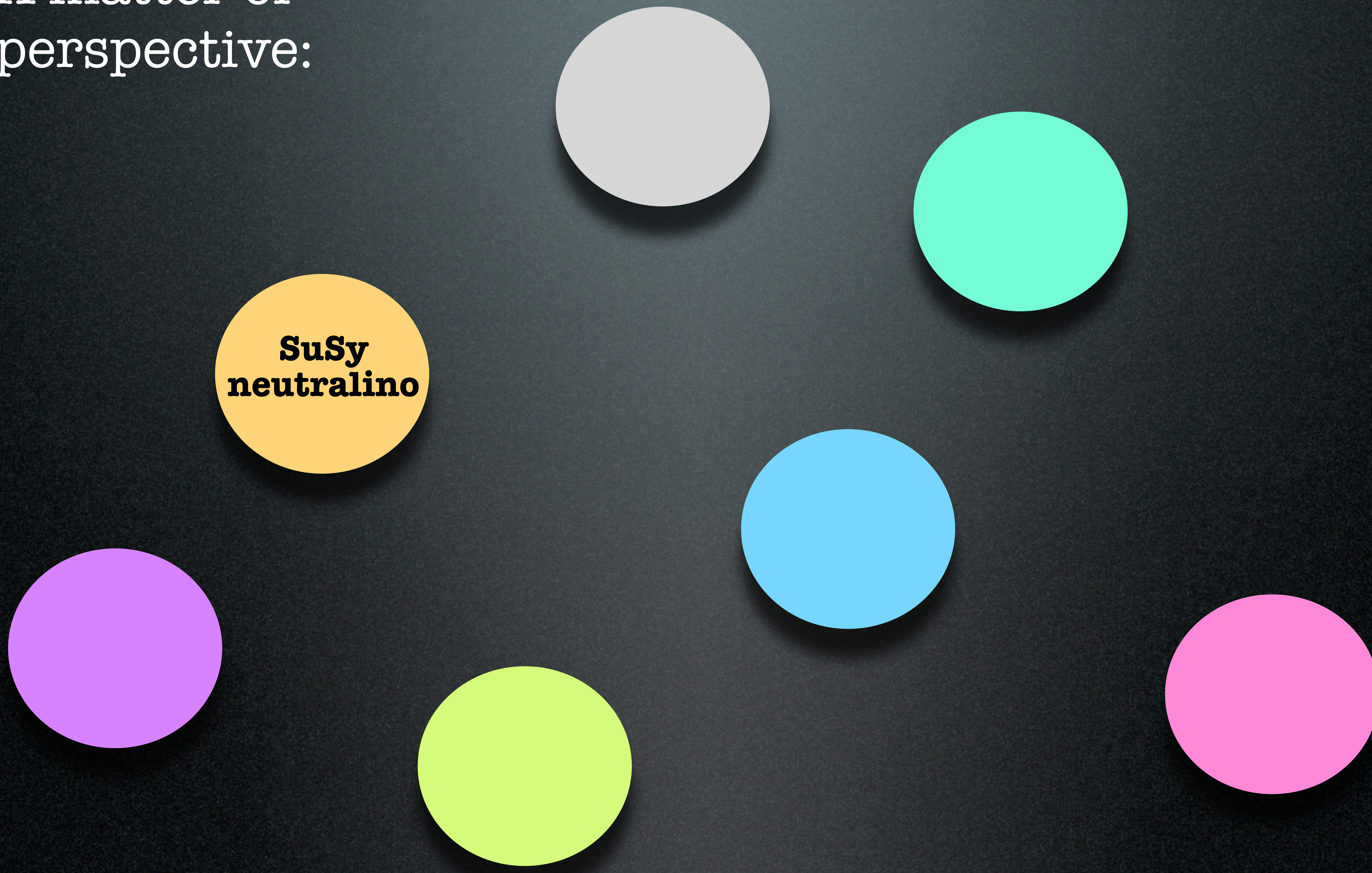
A matter of perspective:

SuSy neutralino

other exotic candi-dates

Introduction

A matter of perspective:



Introduction

A matter of perspective:

Caveat: no categorization is perfect.

DM

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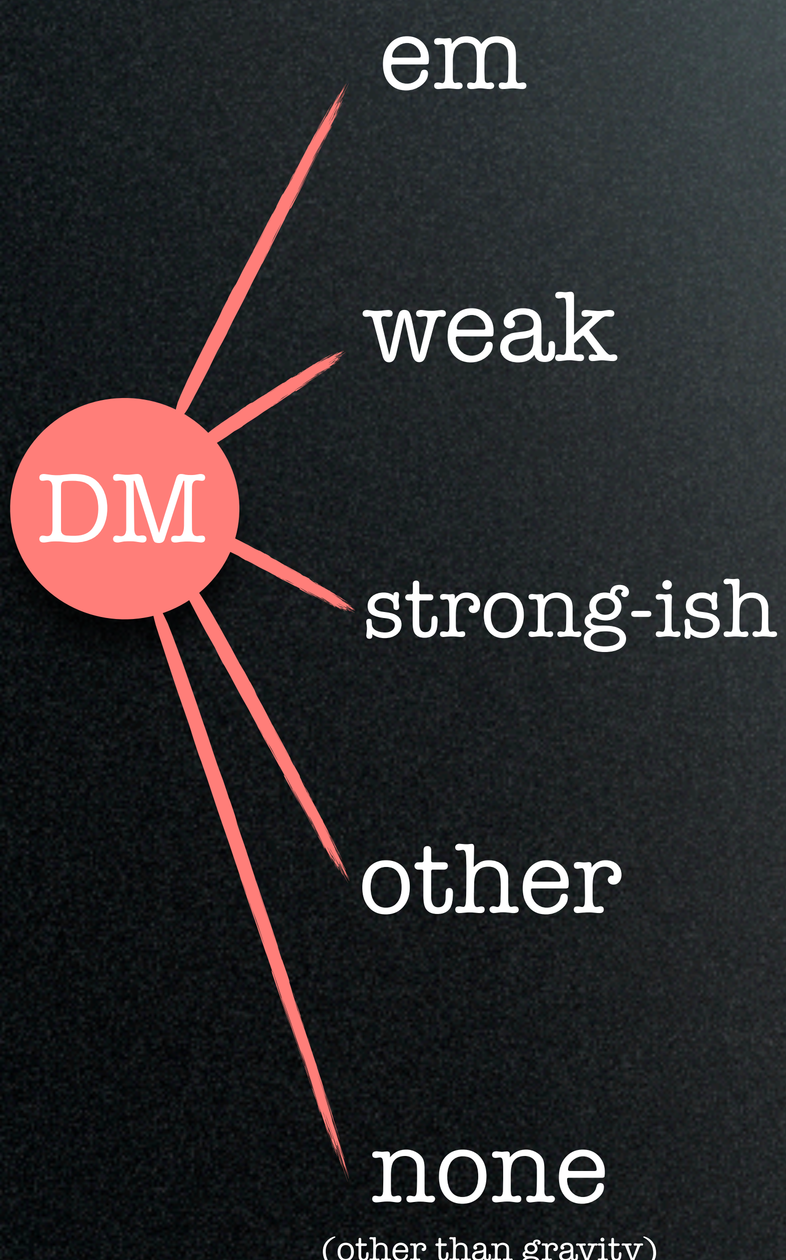

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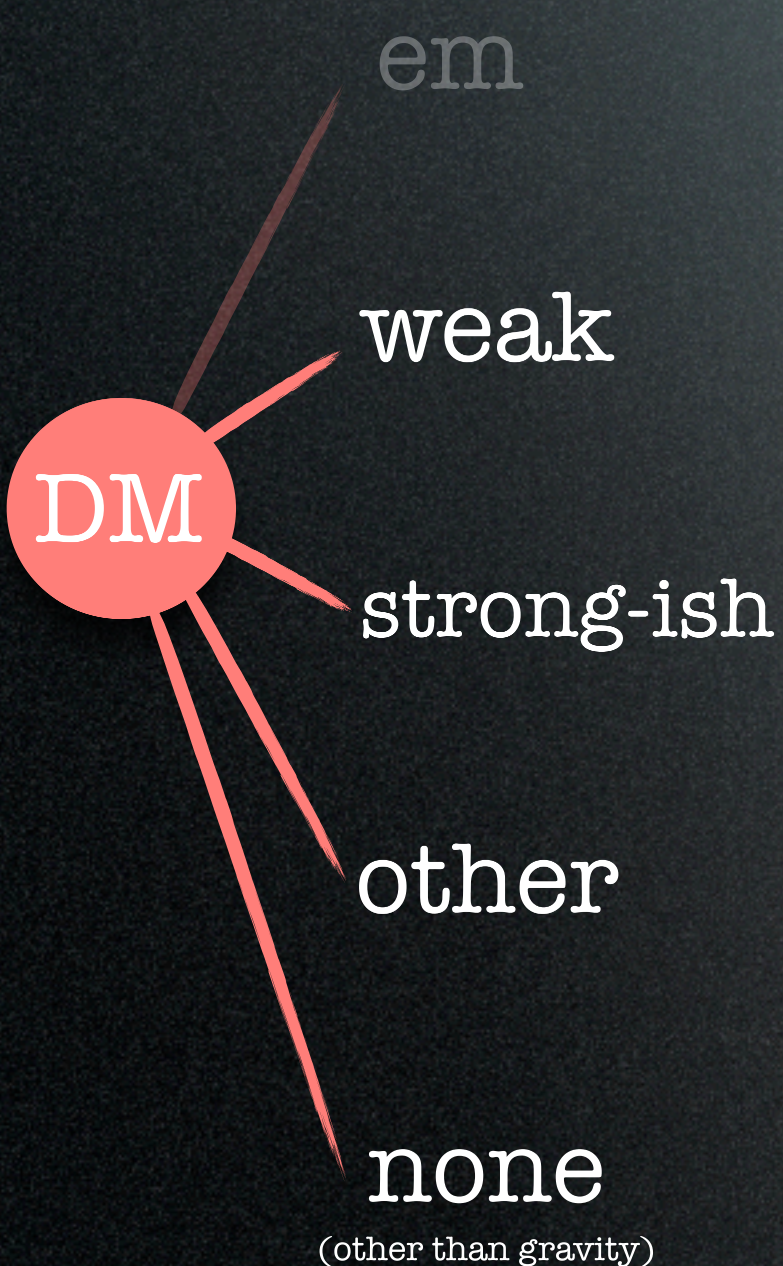

Introduction

A matter of perspective:

Caveat: no categorization is perfect.

Interactions:

- DM
  - em
  - weak
    - neutralino etc
    - Little Higgs DM
    - KK DM
    - Inert Doublet
    - Minimal DM
  - strong-ish
    - TC DM
    - mirror DM
    - (TC DM and mirror DM: aDM)
  - other
    - ‘secluded DM’
    - ‘WIMPless DM’
  - none (other than gravity)
    - singlet scalar
    - sterile neutrino
    - gravitino
    - axion

Introduction

Caveat: no categorization is perfect.

A matter of perspective:

Interactions:

naturalness-inspired

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Introduction

A matter of perspective:

Caveat: no categorization is perfect.

Interactions:		Production mechanism?	Stability?
em			
weak (naturalness-inspired)	neutralino etc	thermal freeze out	R parity
	Little Higgs DM	thermal freeze out	T parity
	KK DM	thermal freeze out	K parity
weak	Inert Doublet	thermal freeze out	Z_2 symmetry
weak	Minimal DM	thermal freeze out	gauge sym
strong-ish	TC DM (aDM)	‘exhaustion’	Tbaryon #
	mirror DM (aDM)	‘exhaustion’	Z_2 symmetry
other	‘secluded DM’	sort of freeze out	some symmetry
	‘WIMPless DM’	sort of freeze out	some symmetry
none (other than gravity)	singlet scalar	thermal freeze out	Z_2 symmetry
	sterile neutrino	mixing	just long lived
	gravitino	thermal or decay	R parity or just long lived
	axion	misalignment?	just long lived

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DM

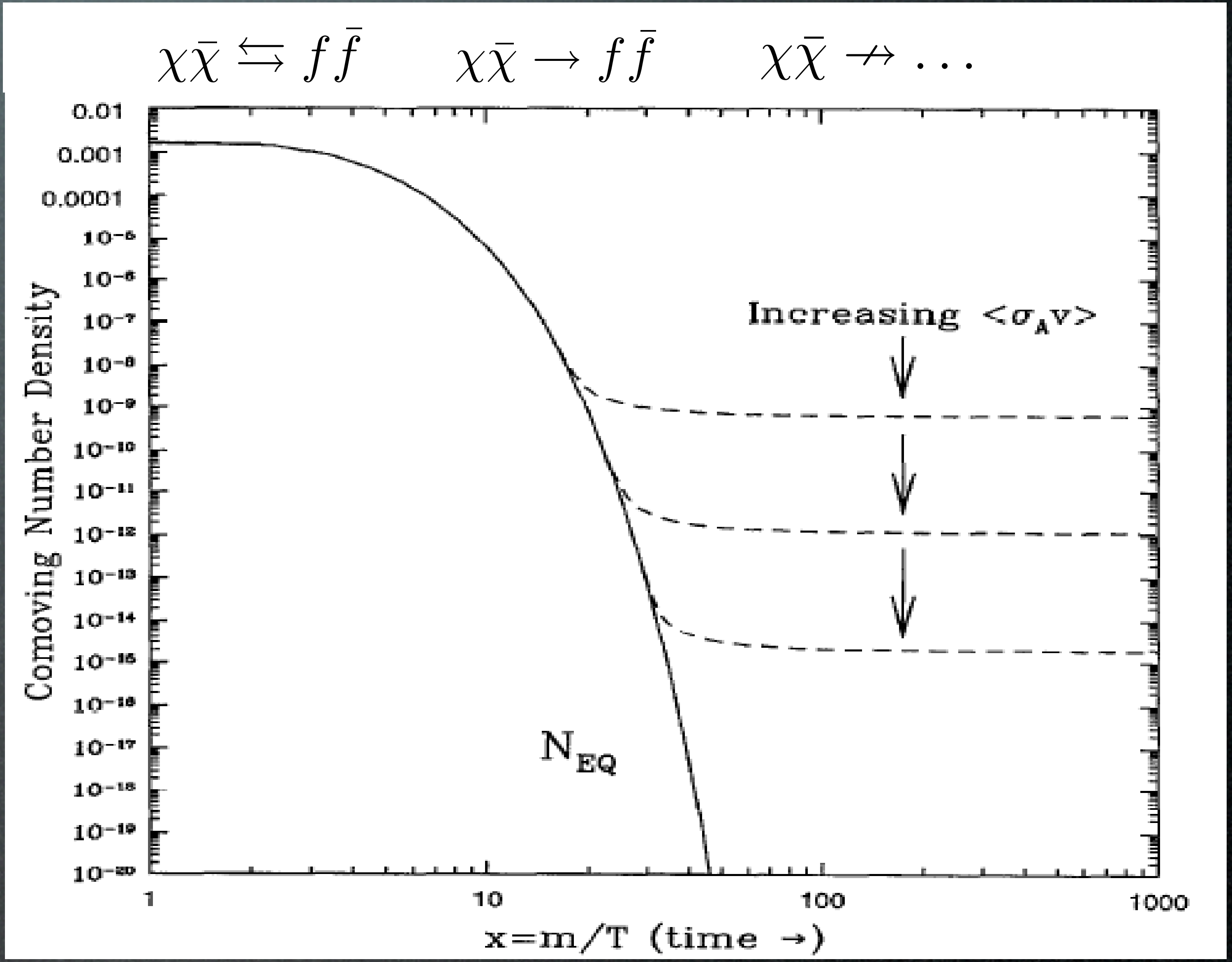
A thermal relic from the Early Universe

Boltzmann equation
in the Early Universe:

$$\Omega_X \approx \frac{6\ 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma_{\mathrm{ann}} v\rangle}$$

Relic $\Omega_{\mathrm{DM}} \simeq 0.23$ for

$$\langle\sigma_{\mathrm{ann}} v\rangle = 3\cdot 10^{-26}\mathrm{cm}^3/\mathrm{sec}$$



Kolb,Turner, The Early Universe, 1995

Weak cross section:

$$\langle\sigma_{\mathrm{ann}} v\rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{\mathbf{1\ TeV}^2} \quad \Rightarrow \Omega_X \sim \mathcal{O}(\text{few } 0.1)$$

(WIMP)

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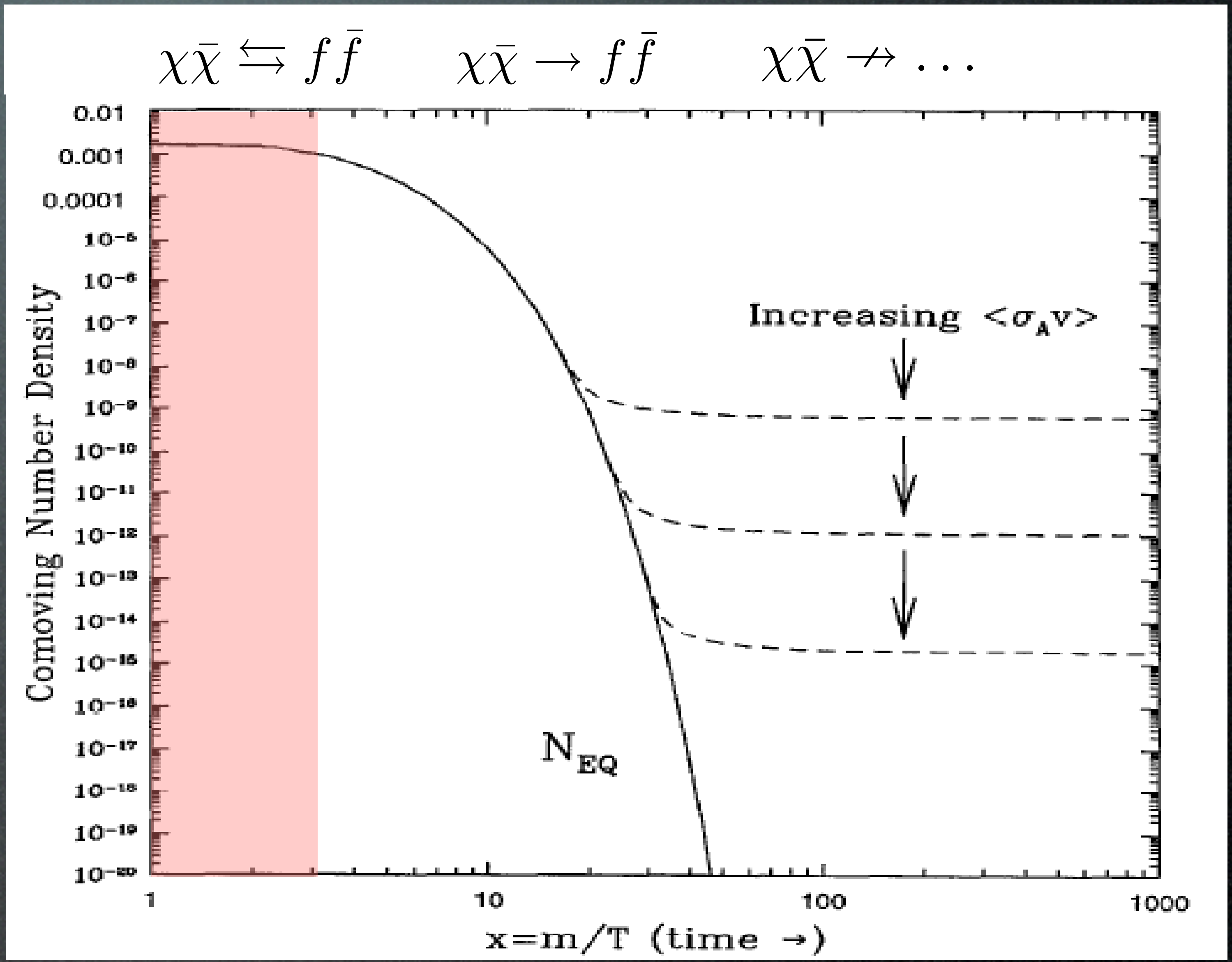

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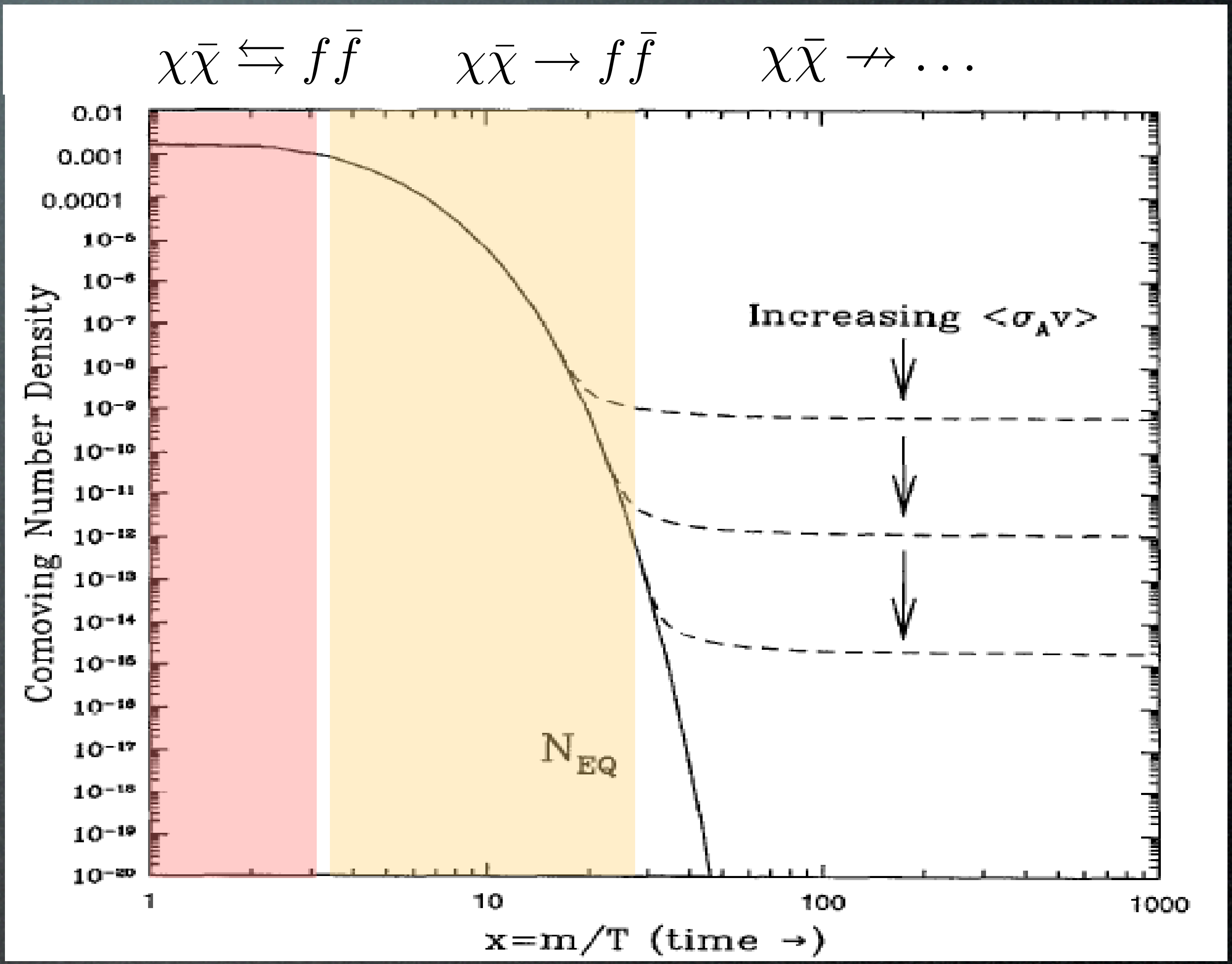

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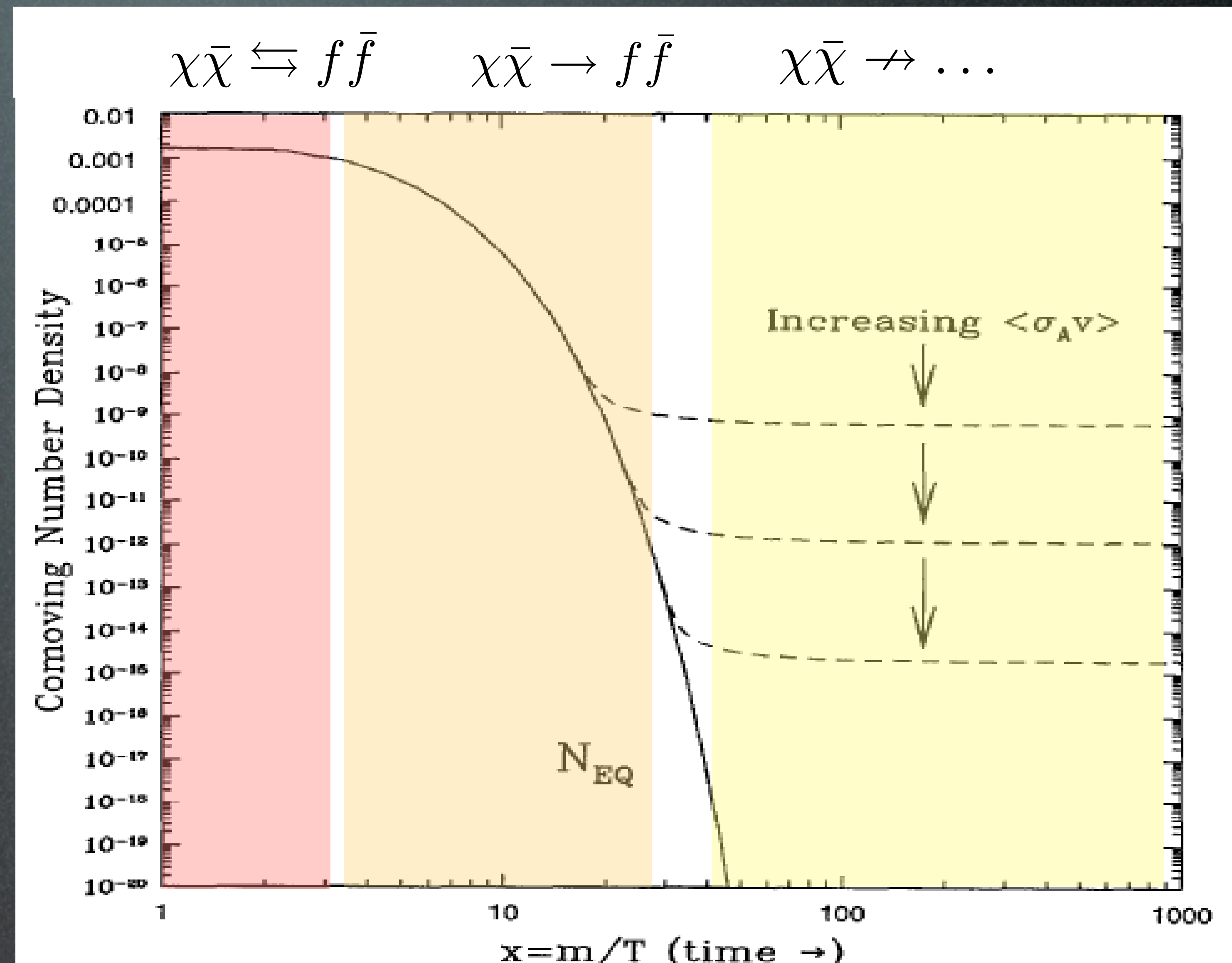

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(WIMP)

Minimal
Dark Matter

Look for a

weakly int., massive, neutral, stable

Theories beyond the SM have ambitious goals (hierarchy prob, EWSB, unification).
As a *byproduct*, they can provide DM candidates at the EW scale.

Popular candidates:

SuperSymmetric LSP,
Little Higgs' heavy photon,
Extra dimensional LKP...

...BUT:

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("little hierarchy problem", ft in LH etc)

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DM phenomenology is unclear (scatter plots)

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("little hierarchy problem", ft in LH etc)

(ii) these theories have many parameters,
DM phenomenology is unclear (scatter plots)

(iii) DM stability is imposed by hand
(R-parity, T-parity, KK parity)

Minimalistic approach

Minimalistic approach

On top of the SM, add only one extra multiplet $\mathcal{X} = \begin{pmatrix} \mathcal{X}_1 \\ \mathcal{X}_2 \\ \vdots \end{pmatrix}$

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \bar{\mathcal{X}}(i\not{D} + M)\mathcal{X}$$ if $\mathcal{X}$ is a fermion

$$\mathscr{L} = \mathscr{L}_{\rm SM} + |D_\mu \mathcal{X}|^2 - M^2|\mathcal{X}|^2$$ if $\mathcal{X}$ is a scalar

and systematically search for the ideal DM candidate...

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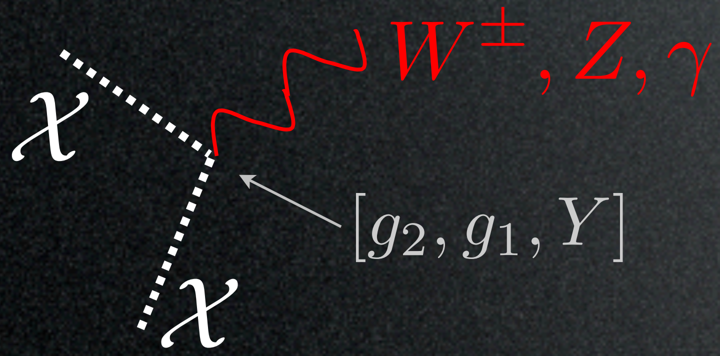
gauge interactions



the only parameter,
and will be fixed by $\Omega_{\rm DM}$.

(other terms in the scalar potential)

(one loop mass splitting)

and systematically search for the ideal DM candidate...

The ideal DM candidate is

weakly int., massive, neutral, stable

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weakly int., massive, neutral, stable

$SU(2)_L$	$U(1)_Y$	spin
$\underline{2}$		
$\underline{3}$		
$\underline{4}$		
$\underline{5}$		
$\underline{7}$		

($\underline{6}$ is similar to $\underline{4}$)

$$\mathcal{X} = \begin{pmatrix} \mathcal{X}_1 \\ \mathcal{X}_2 \\ \vdots \\ \mathcal{X}_n \end{pmatrix}$$

these are all possible choices:

$n \leq 5$ for fermions

$n \leq 7$ for scalars

to avoid explosion in the running coupling

$$\alpha_2^{-1}(E') = \alpha_2^{-1}(M) - \frac{b_2(n)}{2\pi} \ln \frac{E'}{M}$$

The ideal DM candidate is
weakly int., massive, neutral, stable

$SU(2)_L$	$U(1)_Y$	spin
$\underline{2}$	$1/2$	
$\underline{3}$	0	
	1	
$\underline{4}$	$1/2$	
	$3/2$	
$\underline{5}$	0	
	1	
	2	
$\underline{7}$	0	

Each multiplet contains a neutral component with a proper assignment of the hypercharge, according to

$$\boxed{Q = T_3 + Y} \equiv 0$$

e.g. for $n=2$: $T_3 = \begin{pmatrix} +\frac{1}{2} \\ \\ -\frac{1}{2} \end{pmatrix} \Rightarrow |Y| = \frac{1}{2}$

e.g. for $n=3$: $T_3 = \begin{pmatrix} +1 \\ 0 \\ -1 \end{pmatrix} \Rightarrow |Y| = 0 \text{ or } 1$

etc.

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$SU(2)_L$	$U(1)_Y$	spin
$\underline{2}$	$1/2$	S
		F
$\underline{3}$	0	S
		F
	1	S
		F
$\underline{4}$	$1/2$	S
		F
	$3/2$	S
		F
$\underline{5}$	0	S
		F
	1	S
		F
	2	S
		F
$\underline{7}$	0	S

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$SU(2)_L$	$U(1)_Y$	spin	M (TeV)
$\underline{2}$	$1/2$	S	0.43
		F	1.2
$\underline{3}$	0	S	2.0
		F	2.6
	1	S	1.4
		F	1.8
$\underline{4}$	$1/2$	S	2.4
		F	2.5
	$3/2$	S	2.4
		F	2.5
$\underline{5}$	0	S	5.0
		F	4.5
	1	S	3.5
		F	3.2
	2	S	3.5
		F	3.2
$\underline{7}$	0	S	8.5

The mass M is determined by the relic abundance:

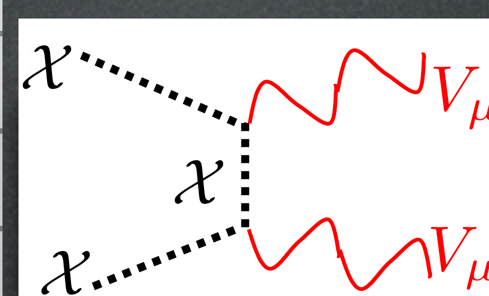
$$\Omega_{\rm DM} = \frac{6\ 10^{-27}{\rm cm}^3{\rm s}^{-1}}{\langle \sigma_{\rm ann} v\rangle} \simeq 0.24$$

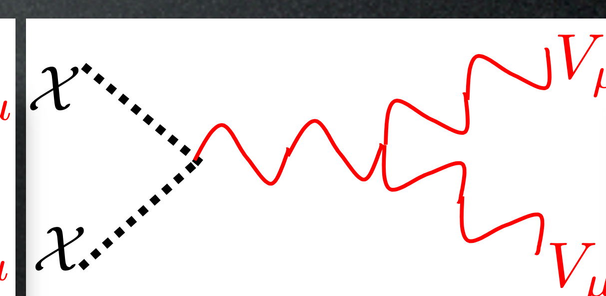
for $\mathcal{X}$ scalar

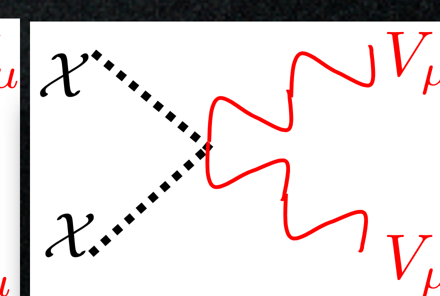
$$\langle \sigma_A v\rangle \simeq \frac{g_2^4\ (3-4n^2+n^4)+16\ Y^4 g_Y^4 + 8 g_2^2 g_Y^2 Y^2 (n^2-1)}{64\pi\ M^2\ g_{\mathcal{X}}}$$

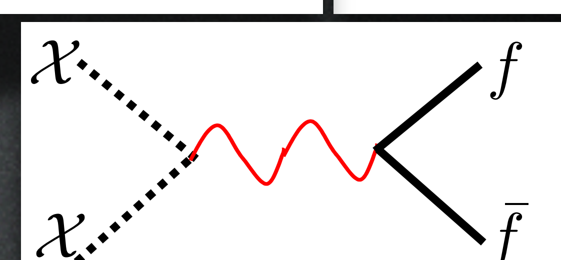
for $\mathcal{X}$ fermion

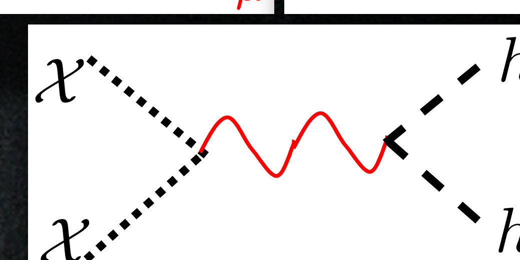
$$\langle \sigma_A v\rangle \simeq \frac{g_2^4\ (2n^4+17n^2-19)+4Y^2 g_Y^4 (41+8Y^2)+16 g_2^2 g_Y^2 Y^2 (n^2-1)}{128\pi\ M^2\ g_{\mathcal{X}}}$$











(- include co-annihilations)
(- computed for $M \gg M_{Z,W}$)

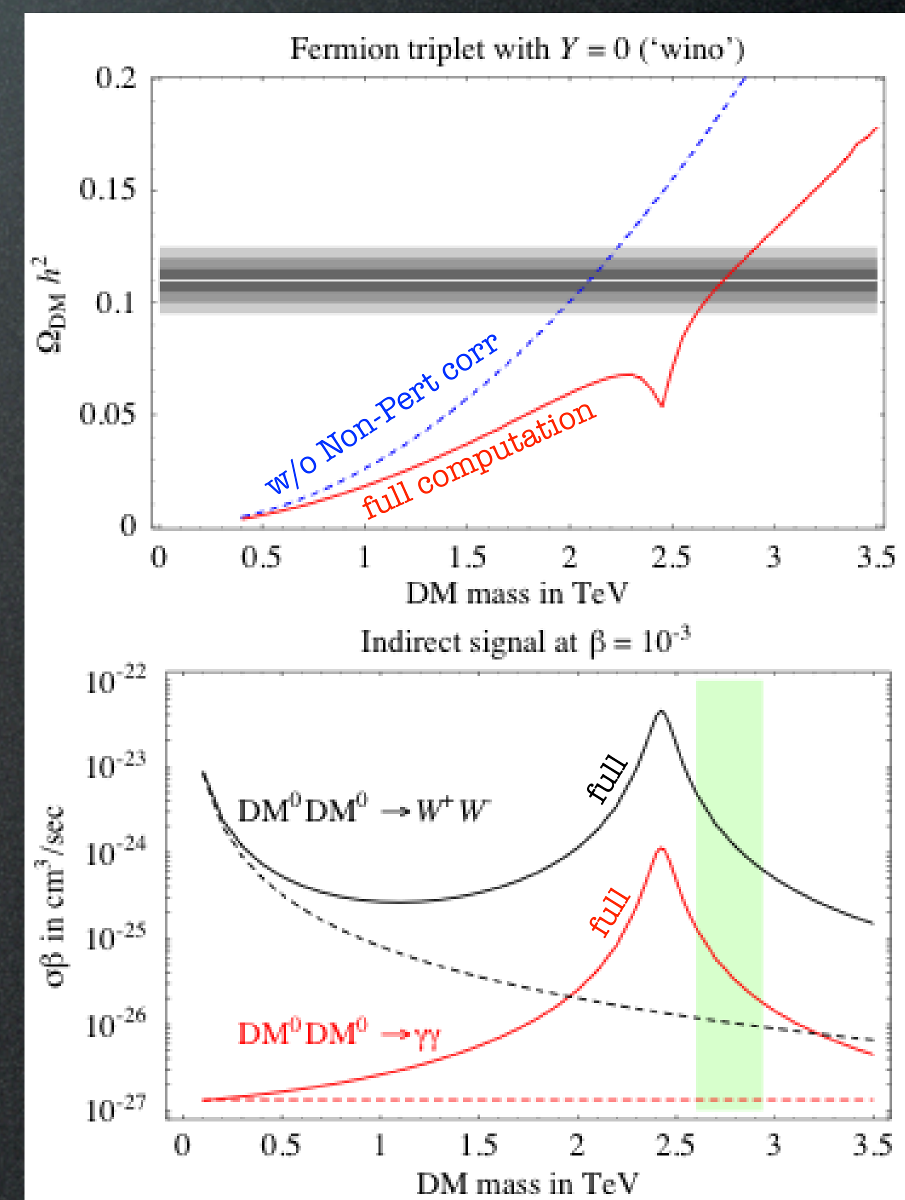
The ideal DM candidate is
weakly int., massive, neutral, stable

$SU(2)_L$	$U(1)_Y$	spin	M (TeV)
$\underline{2}$	1/2	S	
		F	1.0
$\underline{3}$	0	S	2.5
		F	2.7
	1	S	
		F	
$\underline{4}$	1/2	S	
		F	
	3/2	S	
		F	
$\underline{5}$	0	S	9.4
		F	10
	1	S	
		F	
	2	S	
		F	
$\underline{7}$	0	S	25

Non-perturbative corrections
(and other smaller corrections) (more later)
induce modifications:

$$\langle \sigma_{\rm ann} v \rangle \rightsquigarrow R \cdot \langle \sigma_{\rm ann} v \rangle + \langle \sigma_{\rm ann} v \rangle_{p-{\rm wave}}$$

with $R \sim \mathcal{O}(\text{few}) \to \mathcal{O}(10^2)$



The ideal DM candidate is
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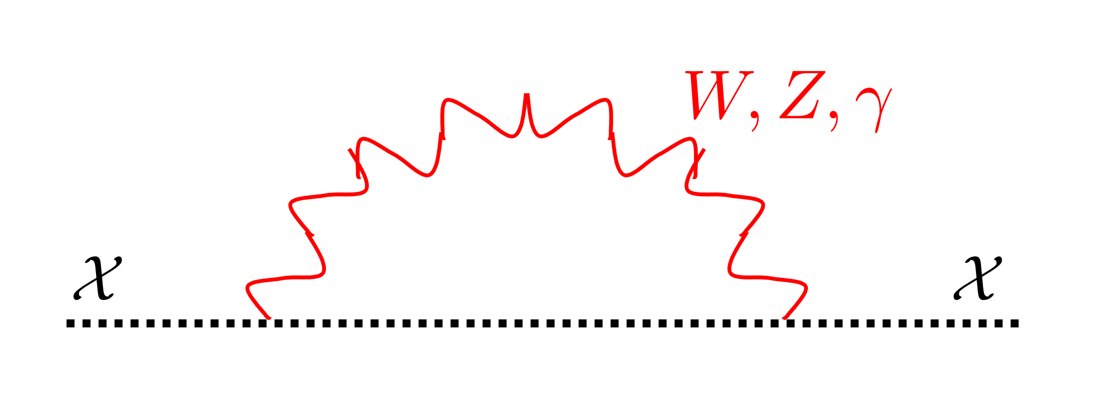
$SU(2)_L$	$U(1)_Y$	spin	M (TeV)	ΔM(MeV)
$\underline{2}$	1/2	S		348
		F	1.0	342
$\underline{3}$	0	S	2.5	166
		F	2.7	166
	1	S		540
		F		526
$\underline{4}$	1/2	S		353
		F		347
	3/2	S		729
		F		712
$\underline{5}$	0	S	9.4	166
		F	10	166
	1	S		537
		F		534
	2	S		906
		F		900
$\underline{7}$	0	S	25	166

EW loops induce a mass splitting ΔM inside the n-uplet:

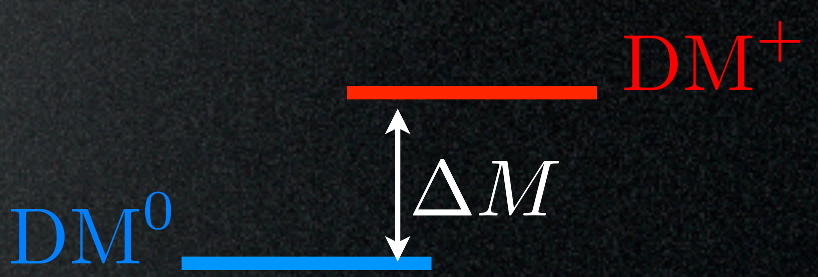
tree level



$$M_Q - M_{Q'} = \frac{\alpha_2 M}{4\pi}\left\{(Q^2 - Q'^2)s_W^2 f(\tfrac{M_Z}{M}) + (Q-Q')(Q+Q'-2Y)\left[f(\tfrac{M_W}{M}) - f(\tfrac{M_Z}{M})\right]\right\}$$

with $f(r) \xrightarrow{r\to 0} -2\pi r$

The neutral component is the lightest



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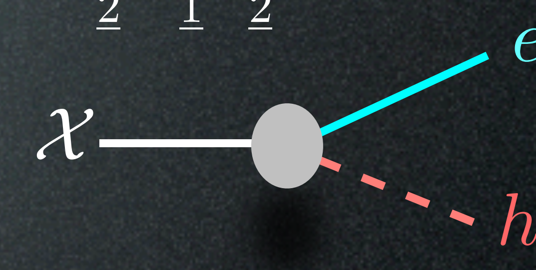
$SU(2)_L$	$U(1)_Y$	spin	M (TeV)	ΔM(MeV)	decay ch.
$\underline{2}$	$1/2$	S		348	EL
		F	1.0	342	EH
$\underline{3}$	0	S	2.5	166	HH^*
		F	2.7	166	LH
	1	S		540	HH, LH
		F		526	LH
$\underline{4}$	$1/2$	S		353	HHH^*
		F		347	(LHH^*)
	$3/2$	S		729	HHH
		F		712	(LHH)
$\underline{5}$	0	S	9.4	166	(HHH^*H^*)
		F	10	166	—
	1	S		537	$(HH^*H^*H^*)$
		F		534	—
	2	S		906	$(H^*H^*H^*H^*)$
		F		900	—
$\underline{7}$	0	S	25	166	—

List all allowed SM couplings:

EH ← e.g. $\overset{1/2}{\underset{\underline{2}}{\chi}}\,\overset{-1}{\underset{\underline{1}}{E}}\,\overset{1/2}{\underset{\underline{2}}{H}}$



(LHH^*) ← e.g. $\overset{1/2}{\underset{\underline{4}}{\chi}}\,\overset{-1/2}{\underset{\underline{2}}{L}}\,\overset{1/2}{\underset{\underline{2}}{H}}\,\overset{-1/2}{\underset{\underline{2}}{H^*}}$

dim=5 operator, induces

$\tau \sim \Lambda^2 \mathrm{TeV}^{-3} \ll t_{\rm universe}$

for $\Lambda \sim M_{\rm Pl}$

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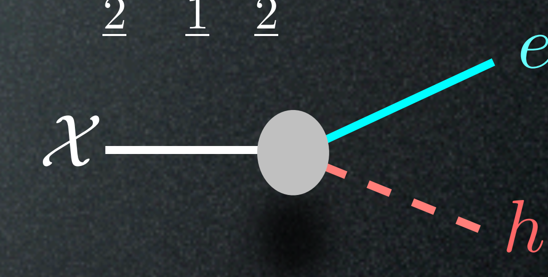

e.g. $\underset{\underline{4}}{\overset{1/2}{\mathcal{X}}}\,\underset{\underline{2}}{\overset{-1/2}{L}}\,\underset{\underline{2}}{\overset{1/2}{H}}\,\underset{\underline{2}}{\overset{-1/2}{H^*}}$

dim=5 operator, induces

$\tau \sim \Lambda^2 \mathrm{TeV}^{-3} \ll t_{\rm universe}$

for $\Lambda \sim M_{\rm Pl}$

No allowed decay!

Automatically stable!

The ideal DM candidate is

weakly int., massive, neutral, stable

and

not excluded

by direct searches!

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	1	S		537	$(HH^*H^*H^*)$
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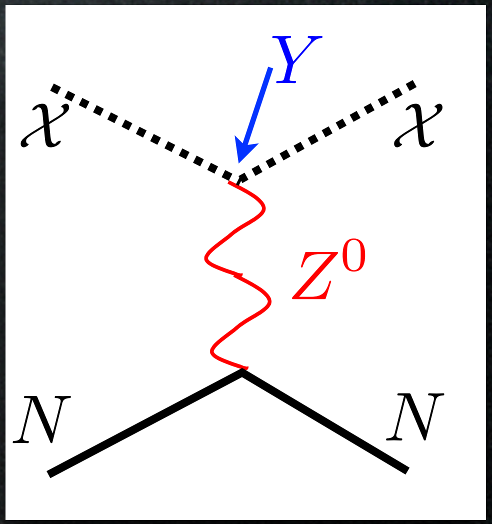
$\underline{4}$	$1/2$	S		353	HHH^*
		F		347	(LHH^*)
	$3/2$	S		729	HHH
		F		712	(LHH)
$\underline{5}$	0	S	9.4	166	(HHH^*H^*)
		F	10	166	—
	1	S		537	$(HH^*H^*H^*)$
		F		534	—
	2	S		906	$(H^*H^*H^*H^*)$
		F		900	—
$\underline{7}$	0	S	25	166	—

and **not excluded** by direct searches!

Candidates with $Y \neq 0$ interact as



$$\sigma \simeq G_F^2 M_N^2 Y^2$$

Goodman Witten 1985

$\gg$ present bounds e.g. Xenon

need $Y = 0$

The ideal DM candidate is

weakly int., massive, neutral, stable

and

not excluded

by direct searches!

$SU(2)_L$	$U(1)_Y$	spin	M (TeV)	ΔM(MeV)	decay ch.
$\underline{2}$	$1/2$	S		348	EL
		F	1.0	342	EH
$\underline{3}$	0	S	2.5	166	HH^*
		F	2.7	166	LH
	1	S		540	HH, LH
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We have a winner!

and a 2° place

(other terms in the scalar potential)

Recap:

A fermionic $SU(2)_L$ quintuplet with $Y = 0$
provides a DM candidate with $M = 10$ TeV,
which is fully successful:
- neutral
- ***automatically*** stable

like proton stability in SM!

and
not yet discovered by DM searches.

A scalar $SU(2)_L$ eptaplet with $Y = 0$ also does.

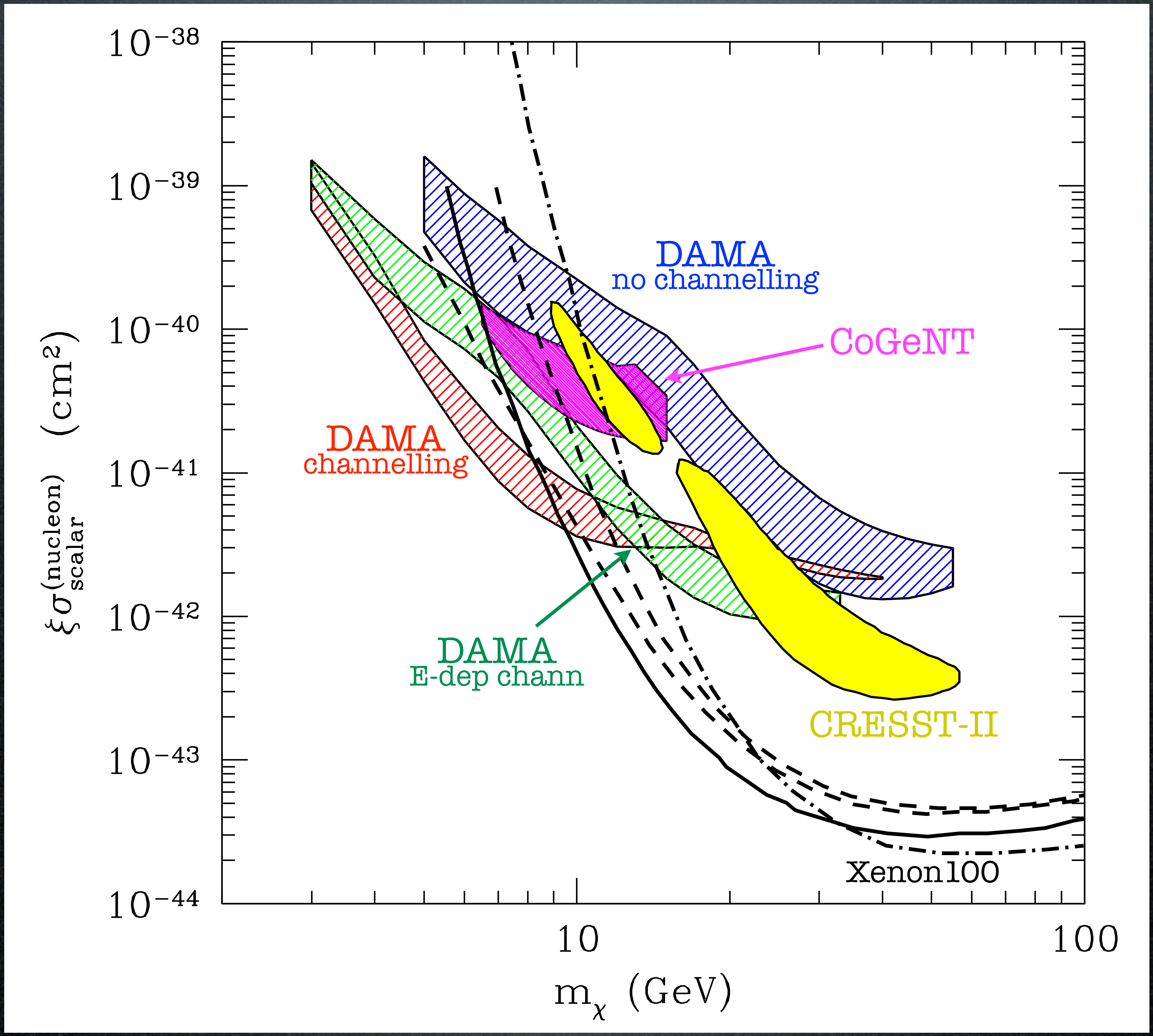
(Other candidates can be cured via non-minimalities.)

Asymmetric Dark Matter

Nussinov 1985
D.B.Kaplan 1992
Farrar, Zaharijas 2005
Zurek 2009
+ many many >2009

A recent motivation

Direct detection seems to prefer low mass DM (few GeV)



Belli+Fornengo+al., 1106.4667

Main motivation

$$\frac{\Omega_{\mathrm{DM}}}{\Omega_{\mathrm{B}}} \simeq 5$$

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Possibly a common production mechanism:

Baryogenesis:

$$\eta_{\rm B} = \frac{n_{\rm B} - n_{\bar{\rm B}}}{n_\gamma} = 6 \cdot 10^{-10}$$

BBN, CMB...

$$\Omega_{\rm B} \propto m_{\rm B}\, \eta_{\rm B}$$

'Darko'genesis:

$$\eta_{\rm DM} = \frac{n_{\rm DM} - n_{\overline{\rm DM}}}{n_\gamma} \overset{?}{=} \eta_{\rm B}$$

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$$\boxed{m_{\rm DM} \simeq 5\ {\rm GeV}}$$

Is this the DM of DAMA, CoGeNT, CRESST?!?

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A variety of specific models/ideas:

- transferring or co-genesis
  cfr J. March-Russell
- DM stores the anti-B number
- via leptogenesis
- connection to neutrino masses

A completely different relic from the Early Universe

Provided:
- an initial asymmetry
- strong enough annihilations

$\chi\bar{\chi} \leftrightarrows f\bar{f} \quad \chi\bar{\chi} \to f\bar{f} \qquad \chi\,? \nrightarrow \ldots$

$$\Omega_{\rm X} \simeq \frac{m_{\rm X}\, s}{\rho_{\rm crit}} \eta_0$$

The relic abundance is determined by η_0 and $m_{\rm X}$.

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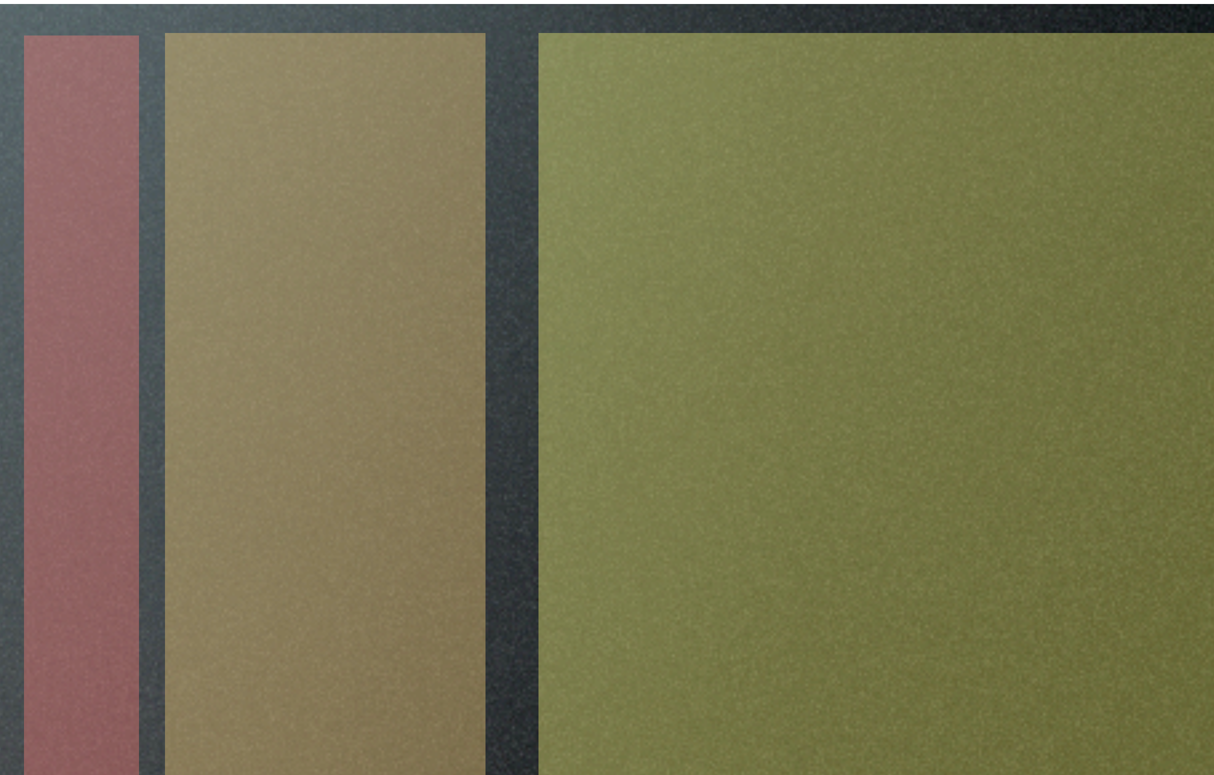

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DETOUR

Asymmetric **Oscillating** DM

Cirelli,
Panci,
Servant,
Zaharijas
1110.3809

Asymmetric Oscillating DM

Cirelli, Panci, Servant, Zaharijas 1110.3809

A small $\mathrm{DM}/\overline{\mathrm{DM}}$ mass splitting induces $\mathrm{DM} \leftrightsquigarrow \overline{\mathrm{DM}}$ oscillations.

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Asymmetric ‘freeze-out’

The correct Ω_{DM} can not be obtained.

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Annihilations restart

Temporary 'freeze-out'

Final freeze-out

The correct Ω_{DM} can be obtained.


DETOUR

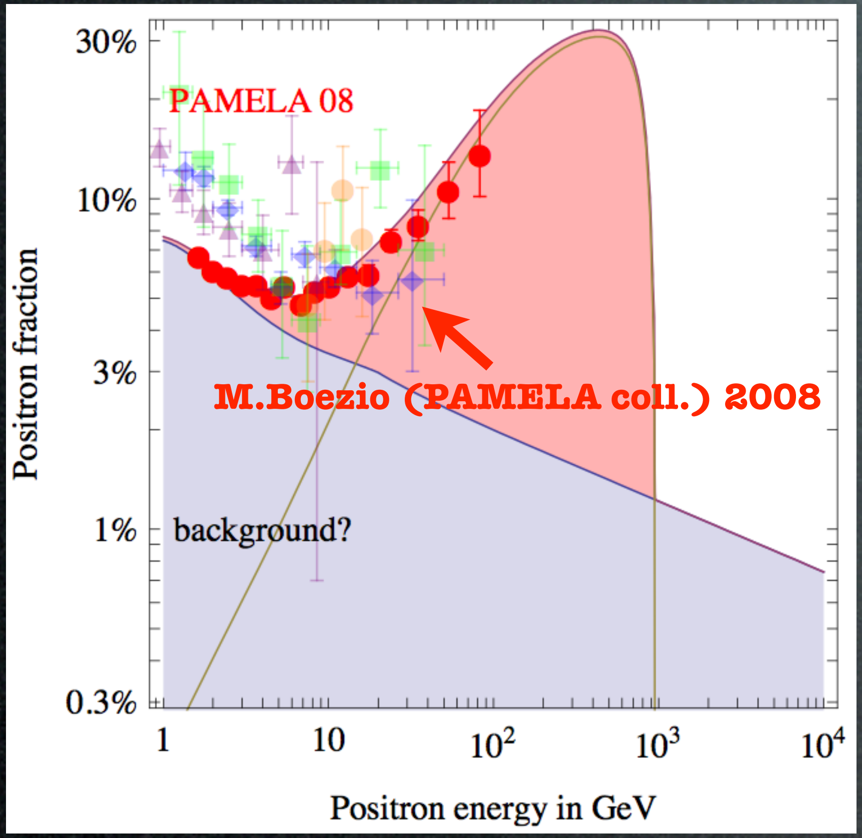
‘Secluded’ Dark Matter

Pospelov, Ritz, Voloshin 2007
Arkani-Hamed, Finkbeiner, Slatyer, Weiner 2008
+ many many **many** >2009

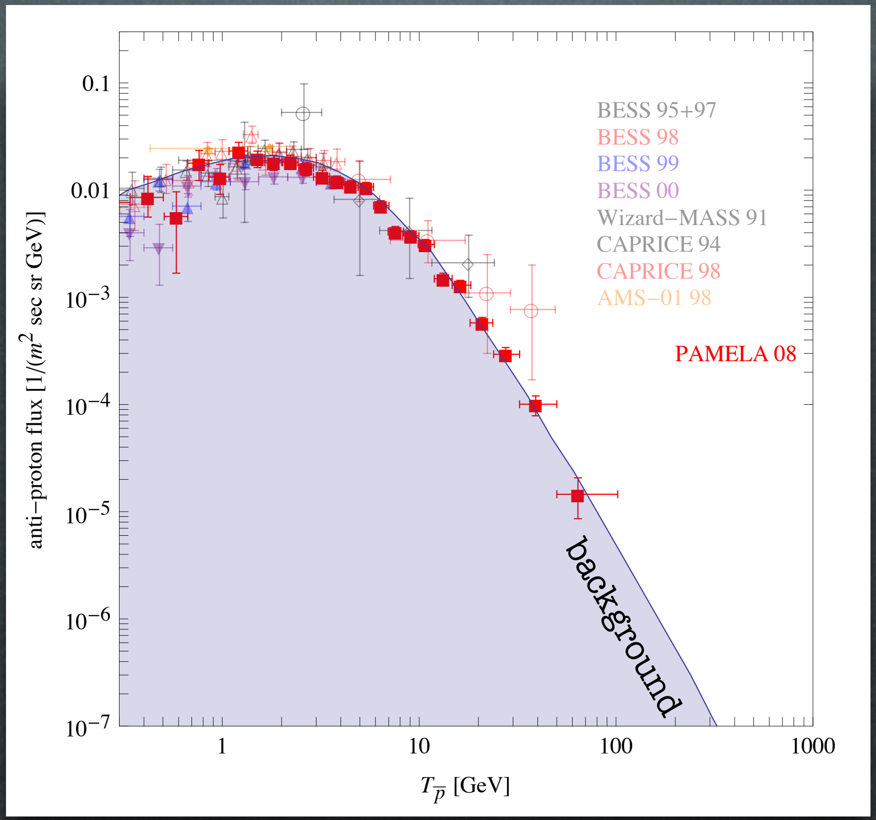
Main motivation

Main motivation

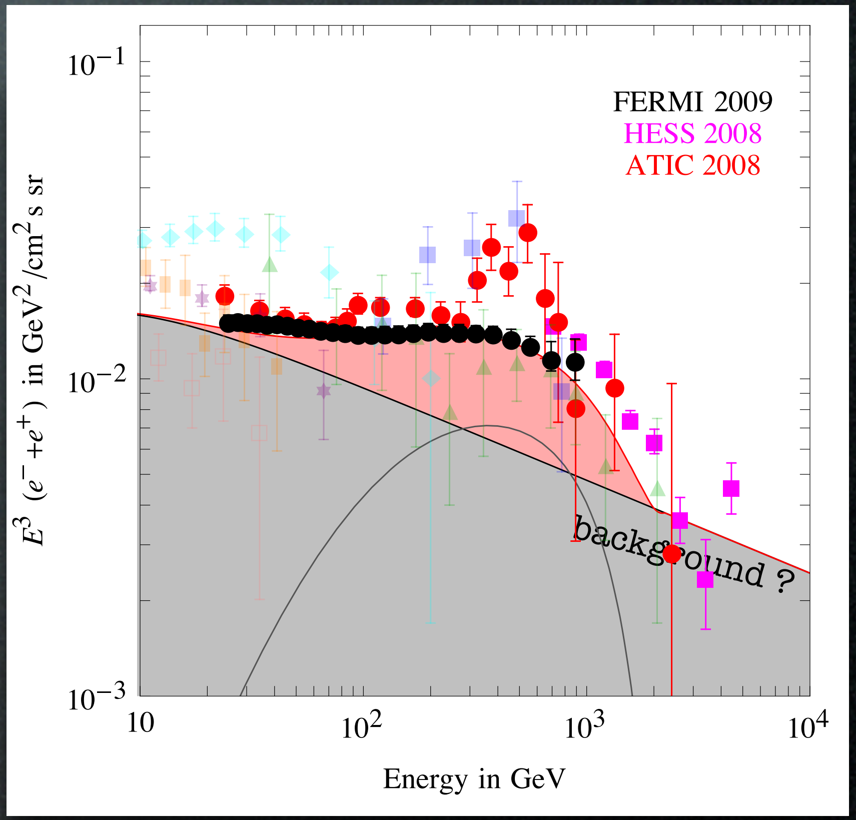
positron fraction



antiprotons



electrons + positrons



Are these signals of Dark Matter?

YES: few TeV, leptophilic DM
with huge $\langle \sigma v \rangle \approx 10^{-23}\, \mathrm{cm}^3/\mathrm{sec}$

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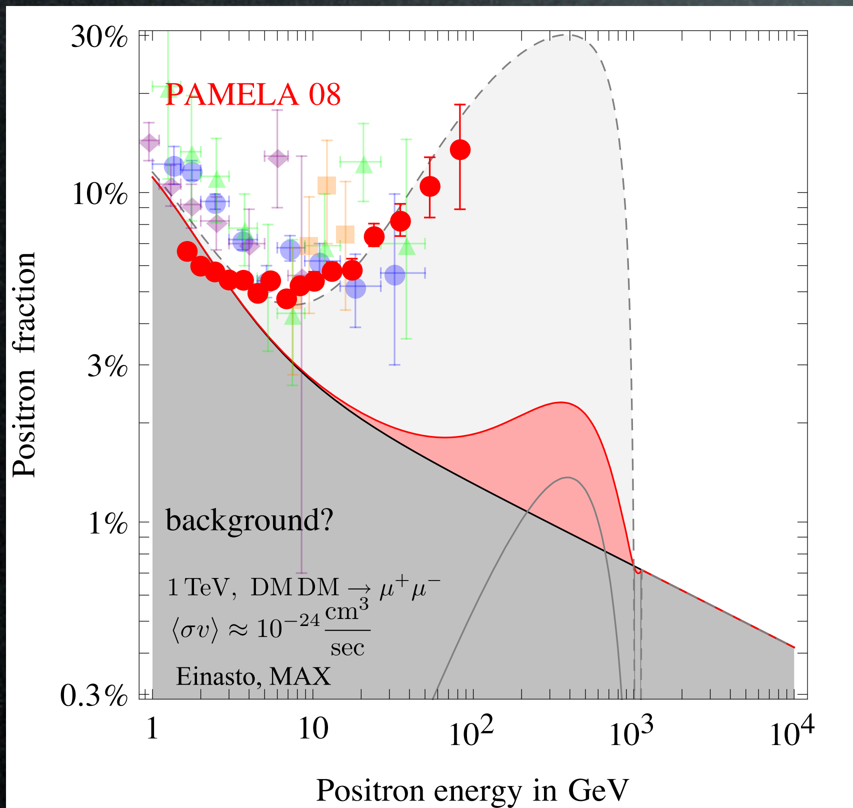

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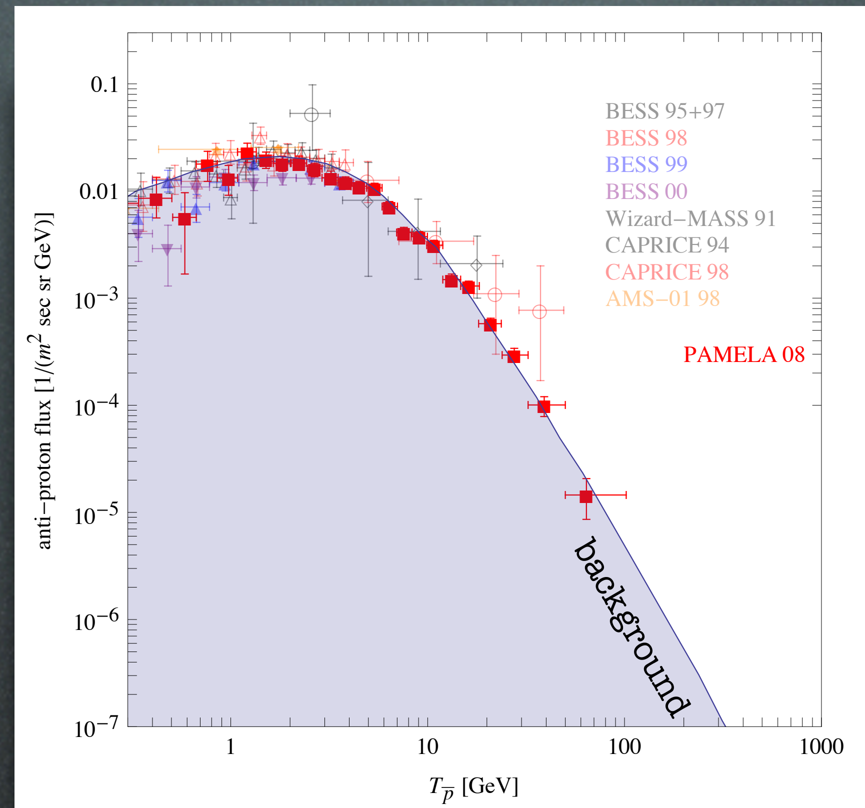

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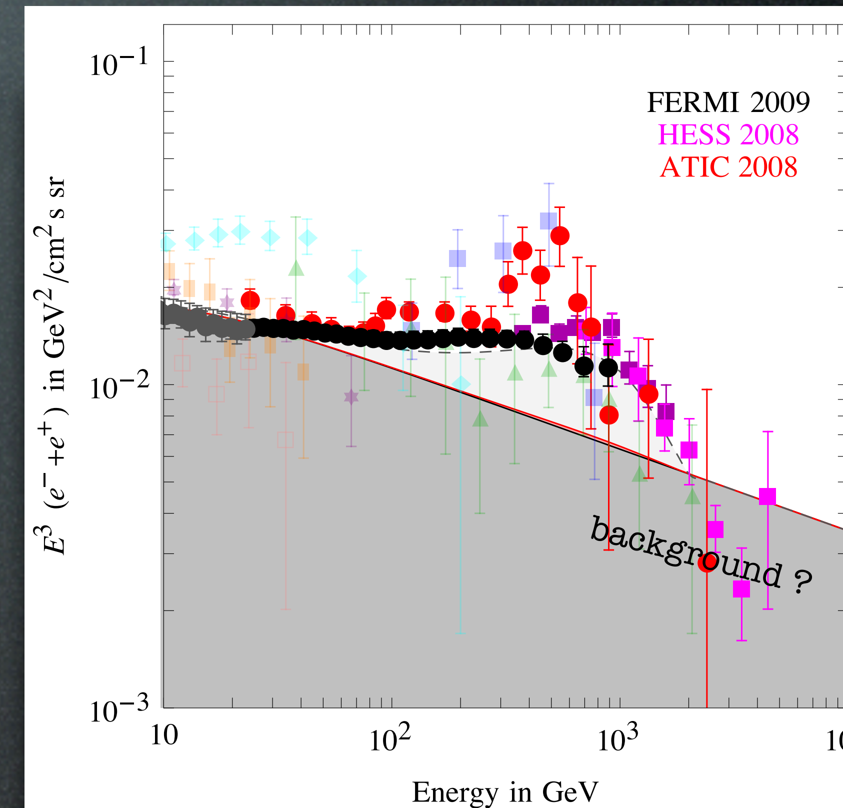

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NO: a formidable ‘background’ for future searches

The "Theory of DM"

Arkani-Hamed, Weiner, Finkbeiner et al. 0810.0713
0811.3641

Basic ingredients:

χ Dark Matter particle, decoupled from SM, mass $M \sim 700+\ \mathrm{GeV}$

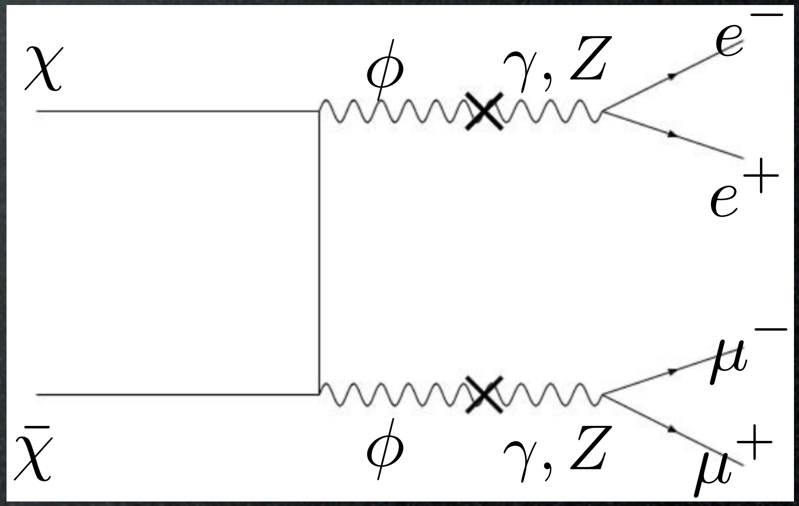
ϕ new gauge boson ("Dark photon"),

couples only to DM, with typical gauge strength, $m_\phi \sim \mathrm{few\ GeV}$

- mediates Sommerfeld enhancement of $\chi\bar{\chi}$ annihilation:

$\alpha M/m_V \gtrsim 1$ fulfilled

- decays only into e^+e^- or $\mu^+\mu^-$
for kinematical limit



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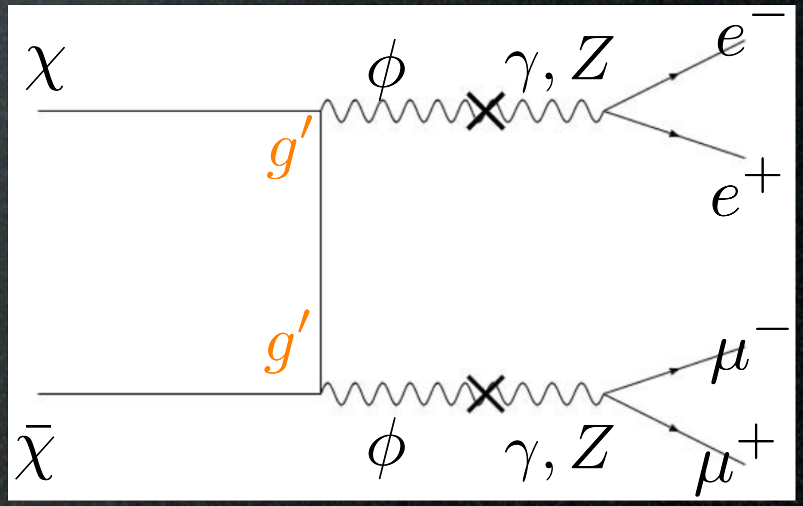

Production mechanism:

just thermal freeze-out of these annihilations

same idea in: WIMPless DM Feng, Kumar 2008

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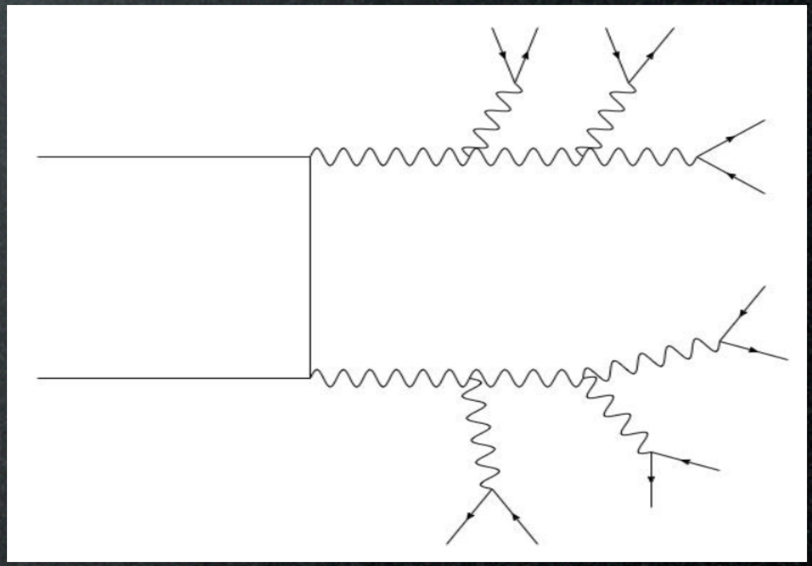


Extras:

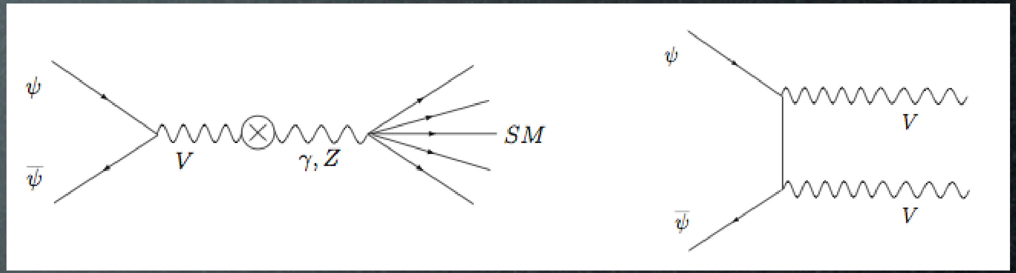
χ is a multiplet of states and ϕ is non-abelian gauge boson:
splitting $\delta M \sim 200\ \mathrm{KeV}$ (via loops of non-abelian bosons)
- inelastic scattering explains DAMA
- eXcited state decay $\chi\chi \to \chi\chi^*$ explains INTEGRAL
$\hookrightarrow e^+e^-$

Variations

(selected)

- pioneering: Secluded DM, U(1) Stückelberg extension of SM

  Pospelov, Ritz et al 0711.4866 P.Nath et al 0810.5762



- Axion Portal: ϕ is pseudoscalar axion-like

  Nomura, Thaler 0810.5397

- singlet-extended UED: χ is KK RNnu, ϕ is an extra bulk singlet

  Bai, Han 0811.0387

- split UED: χ annihilates only to leptons because quarks are on another brane

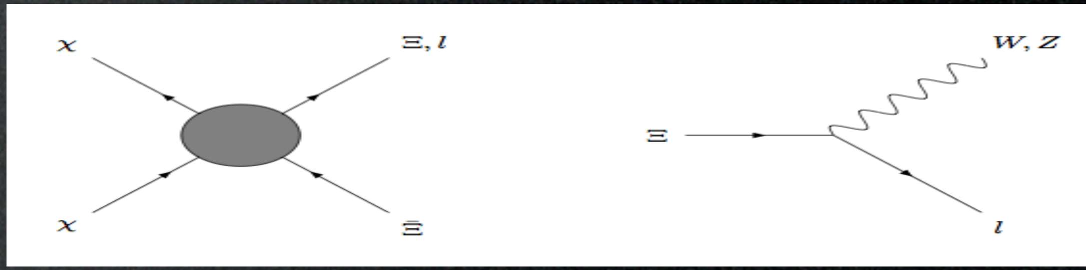
  Park, Shu 0901.0720

- DM carrying lepton number: χ charged under $U(1)_{L_\mu - L_\tau}$, ϕ gauge boson

  Cirelli, Kadastik, Raidal, Strumia 0809.2409 Fox, Poppitz 0811.0399 $(m_\phi \sim \text{tens GeV})$

- New Heavy Lepton: χ annihilates into Ξ that carries lepton number and decays weakly $(\sim \text{TeV})$ $(\sim \text{100s GeV})$

  Phalen, Pierce, Weiner 0901.3165



- ......

[jump to conclusions]

Sommerfeld Enhancement

NP QM effect that can enhance the annihilation cross section by orders of magnitude in the regime of small velocity and relatively long range force.

Sommerfeld, Ann.Phys. 403, 257 (1931)

Hisano et al., 2003-2006:
in part. hep-ph/0307216, 0412403, 0610249

Cirelli, Tamburini, Strumia 0706.4071

Arkani-Hamed et al., 0810.0713

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A classical analogy:

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$$\sigma_0 = \pi R^2$$

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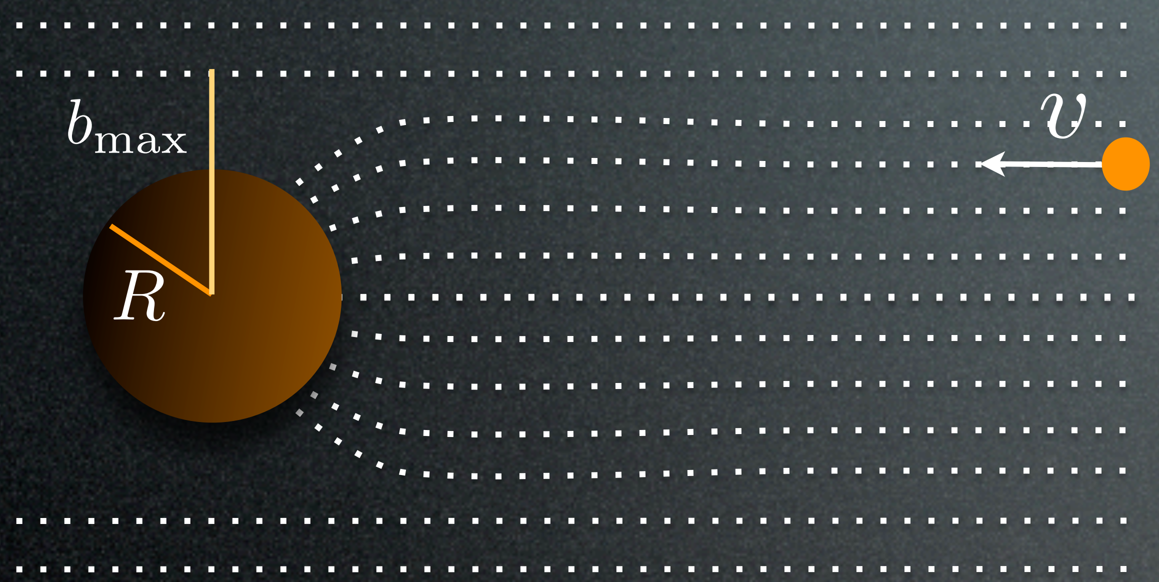

$$\sigma_0 = \pi R^2$$

$$\sigma = \pi R^2 \left(1 + \frac{2 G_N M/R}{v^2} \right)$$

with $v_{\rm esc}^2 = 2 G_N M/R$

For $v \gg v_{\rm esc}$ then $\sigma \to \sigma_0$

For $v \ll v_{\rm esc}$ then $\sigma \gg \sigma_0$

i.e. $E_{\rm kin} < U_{\rm pot}$ (i.e. the deforming potential is not negligible)

[jump to conclusions]

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Cirelli, Strumia, Tamburini 0706.4071

$\psi(\vec{r})$ wave function of two DM particles ($\vec{r} = \vec{r}_1 - \vec{r}_2$)

obeys (reduced) Schrödinger equation:

(V does not depend on time)

$$-\frac{1}{M}\frac{d^2\psi}{dr^2} + V \cdot \psi = M\nu^2\psi$$

velocity

potential due to exchange of force carriers

At $r = 0$: annihilation

$$\sigma_{\mathrm{ann}} \propto \psi\Gamma\psi$$ with Γ such that $\langle \mathrm{DM}\,\mathrm{DM}|\Gamma|\mathrm{final}\rangle$

Sommerfeld enhancement:

$$R = \frac{\sigma_{\mathrm{ann}}}{\sigma^0_{\mathrm{ann}}} = \left|\frac{\psi(\infty)}{\psi(0)}\right|^2$$

unperturbed cross section

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Yukawa potential:

Cirelli, Strumia, Tamburini 0706.4071

$$-\frac{1}{M}\frac{d^2\psi}{dr^2} + V \cdot \psi = M\nu^2\psi$$

with $V = -\frac{\alpha}{r}e^{-m_V\, r}$

parameters are: α, ν, m_V, M $\left(\alpha = \frac{g^2}{4\pi} \approx \frac{1}{137}\right)$

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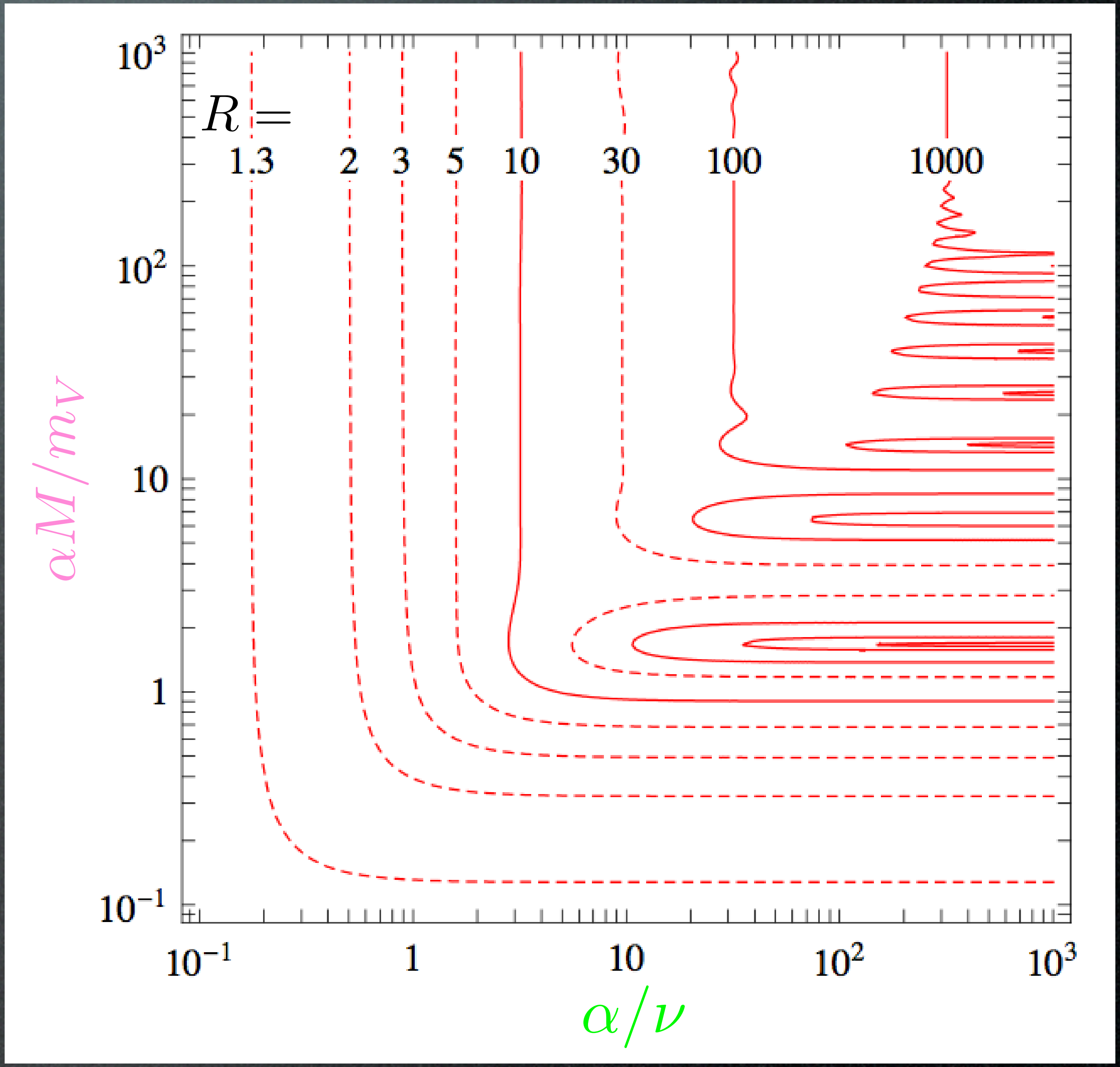

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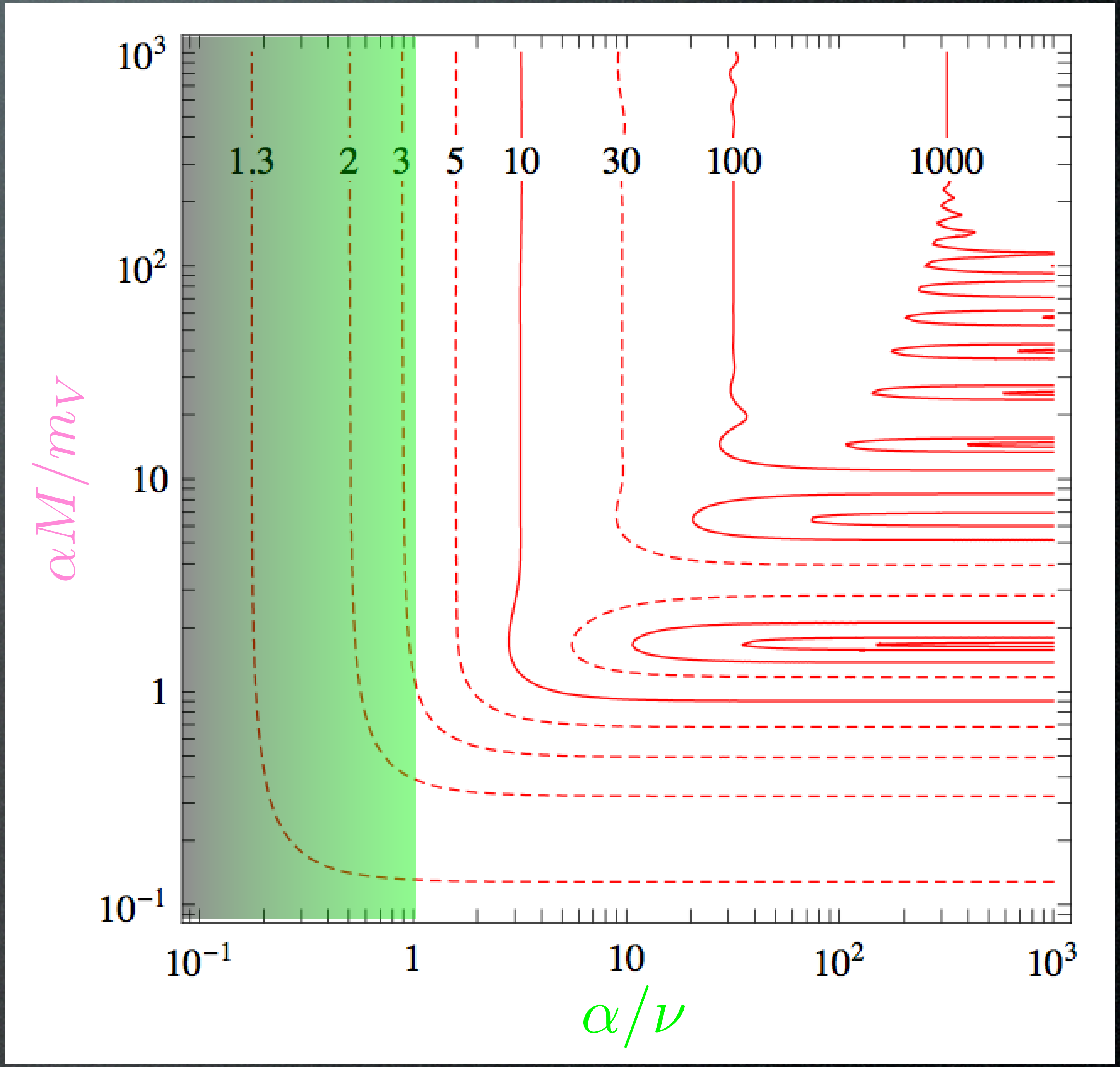
The effect is relevant for:

$\alpha/\nu \gtrsim 1$ i.e. small velocities
i.e today but not at f.o.

Cirelli, Strumia, Tamburini 0706.4071



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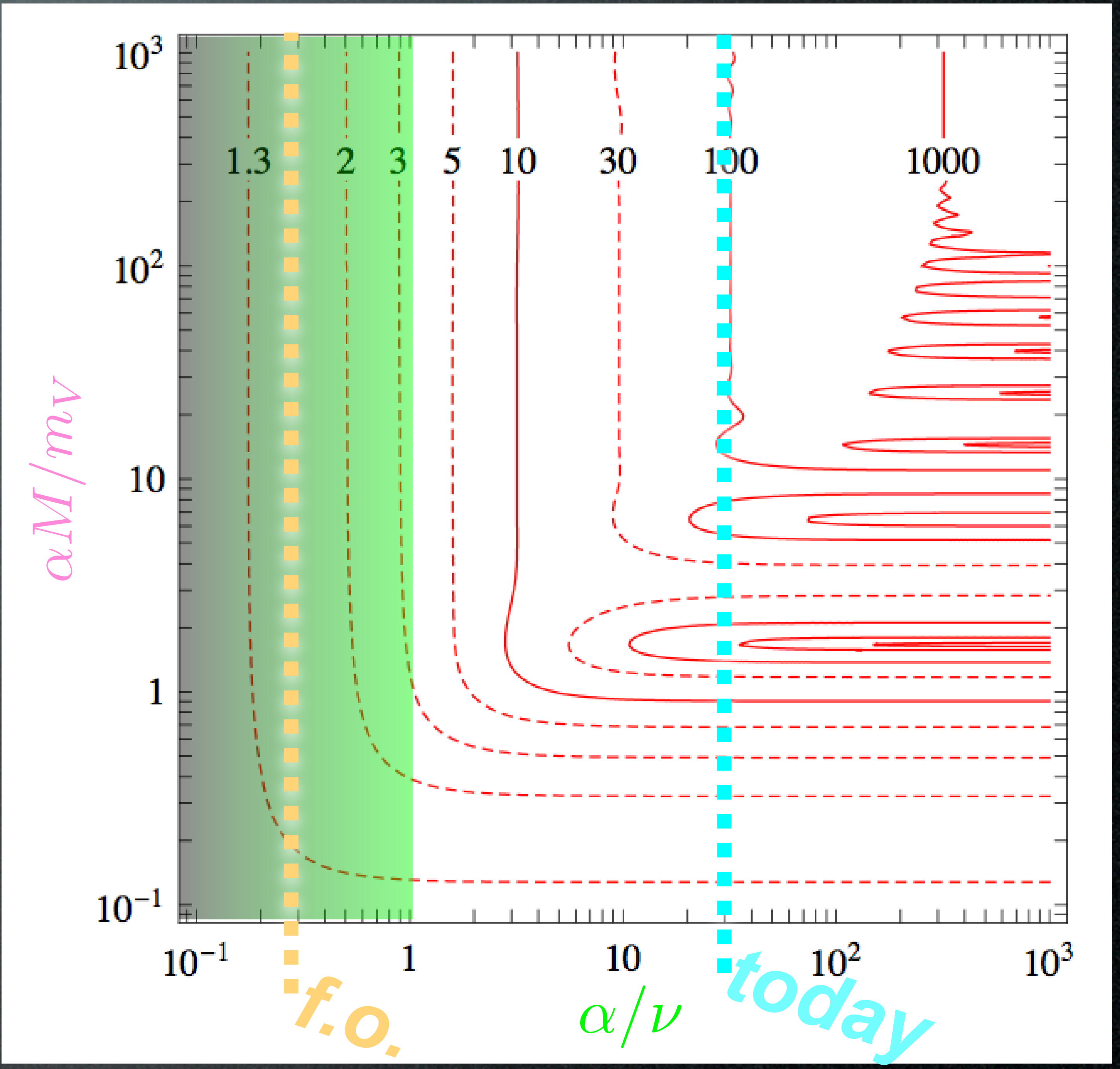

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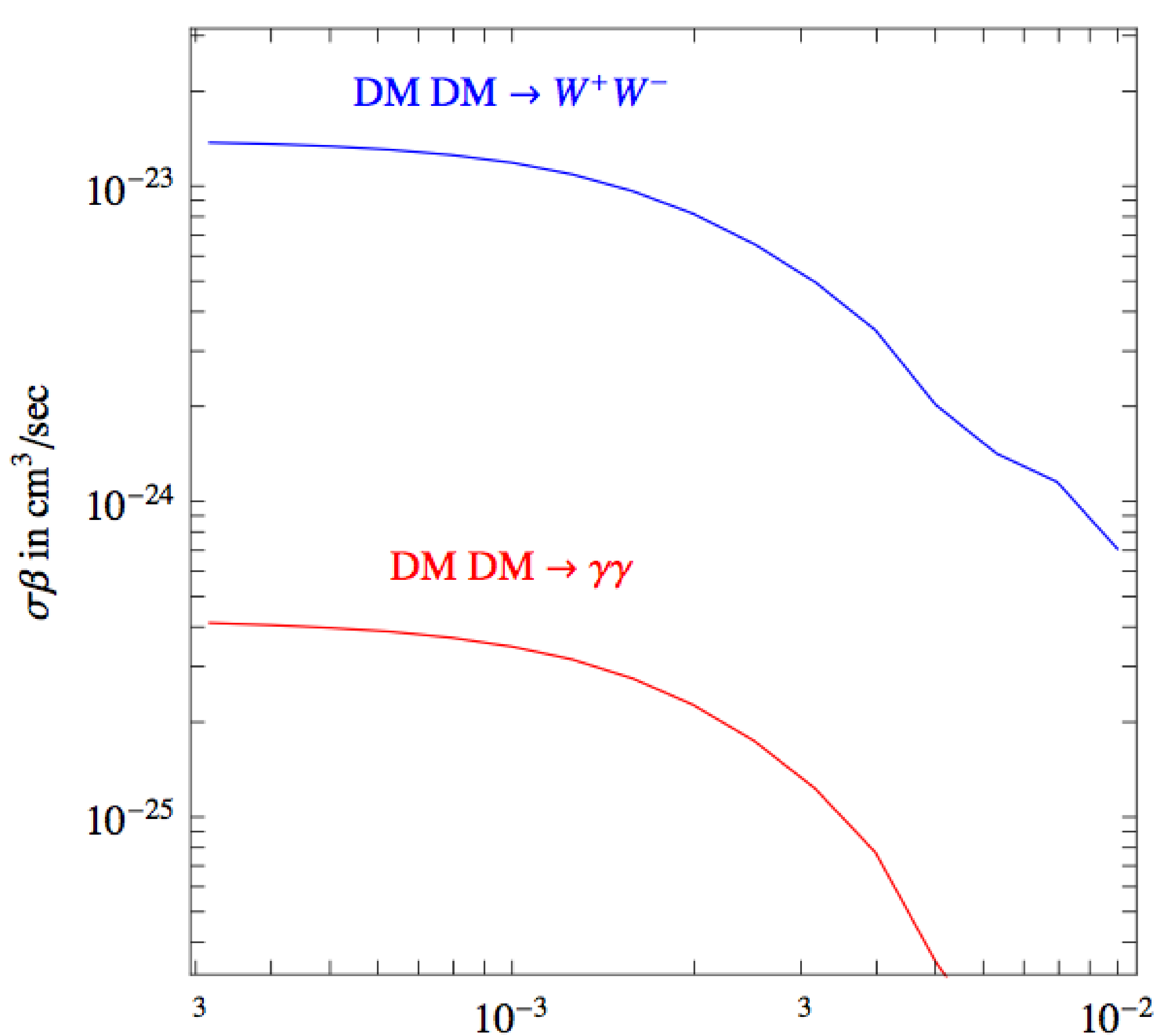
i.e today but not at f.o.

Cirelli, Strumia, Tamburini 0706.4071
Cirelli, Franceschini, Strumia 0802.3378



case of MDM fermion 5-plet:
M=9.7 TeV, W,Z exchange

Sommerfeld Enhancement

NP QM effect that can enhance the annihilation cross section by orders of magnitude in the regime of small velocity and relatively long range force.

Yukawa potential:

Cirelli, Strumia, Tamburini 0706.4071
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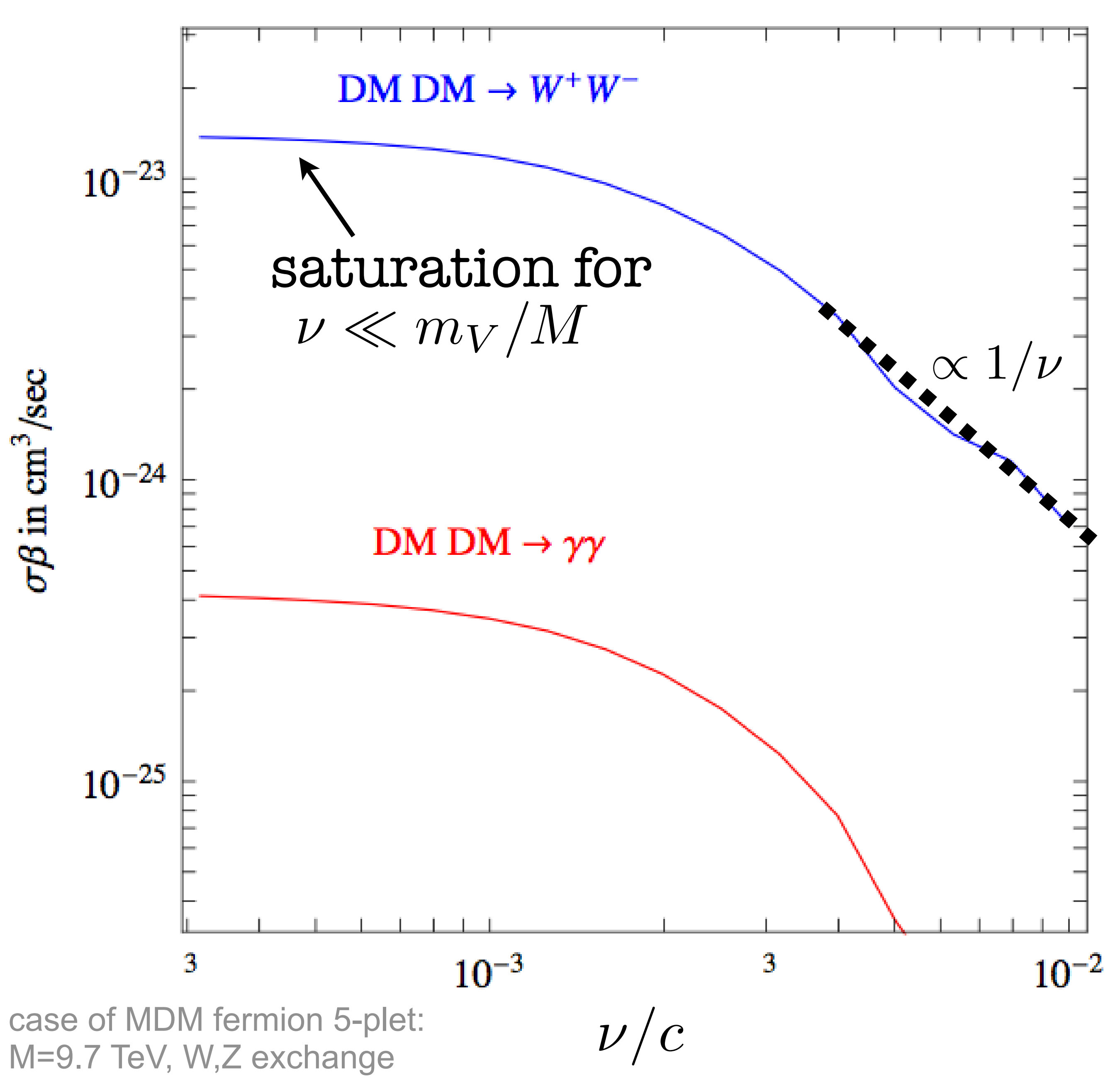

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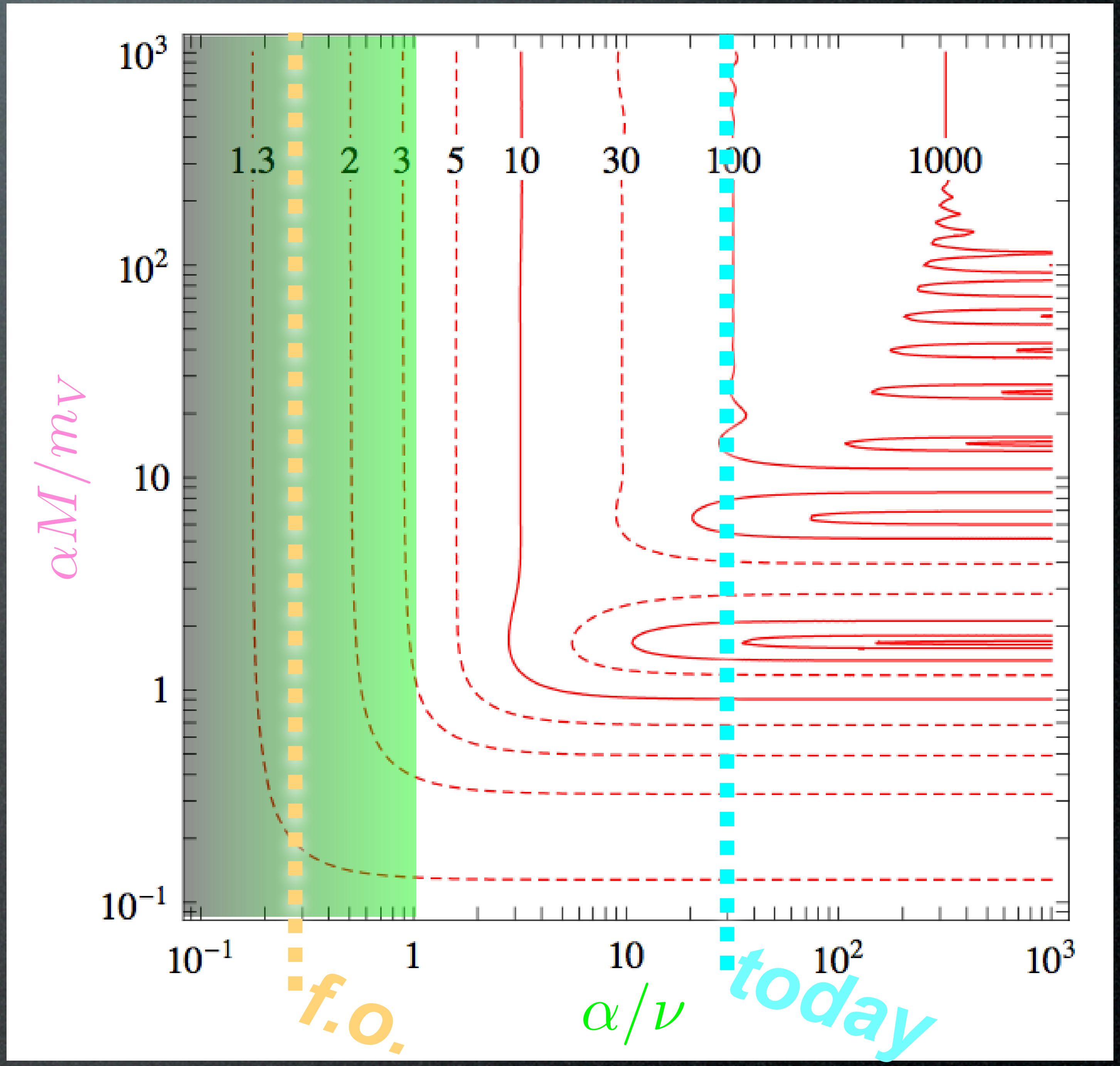

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for SM weak: $\quad m_V \to M_{W,Z}$
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for 1 TeV DM: need $\; m_V \to \text{GeV}$

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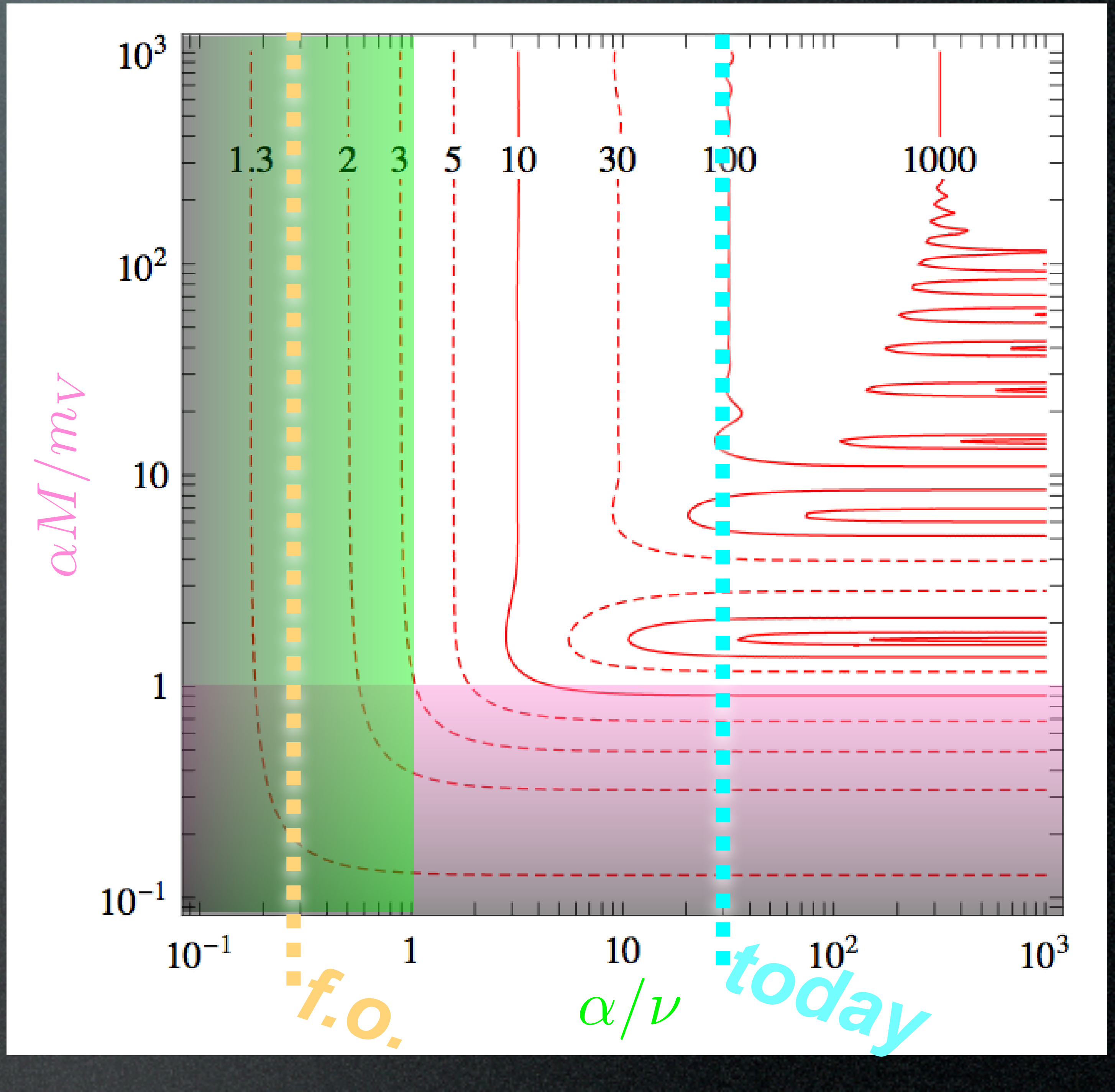

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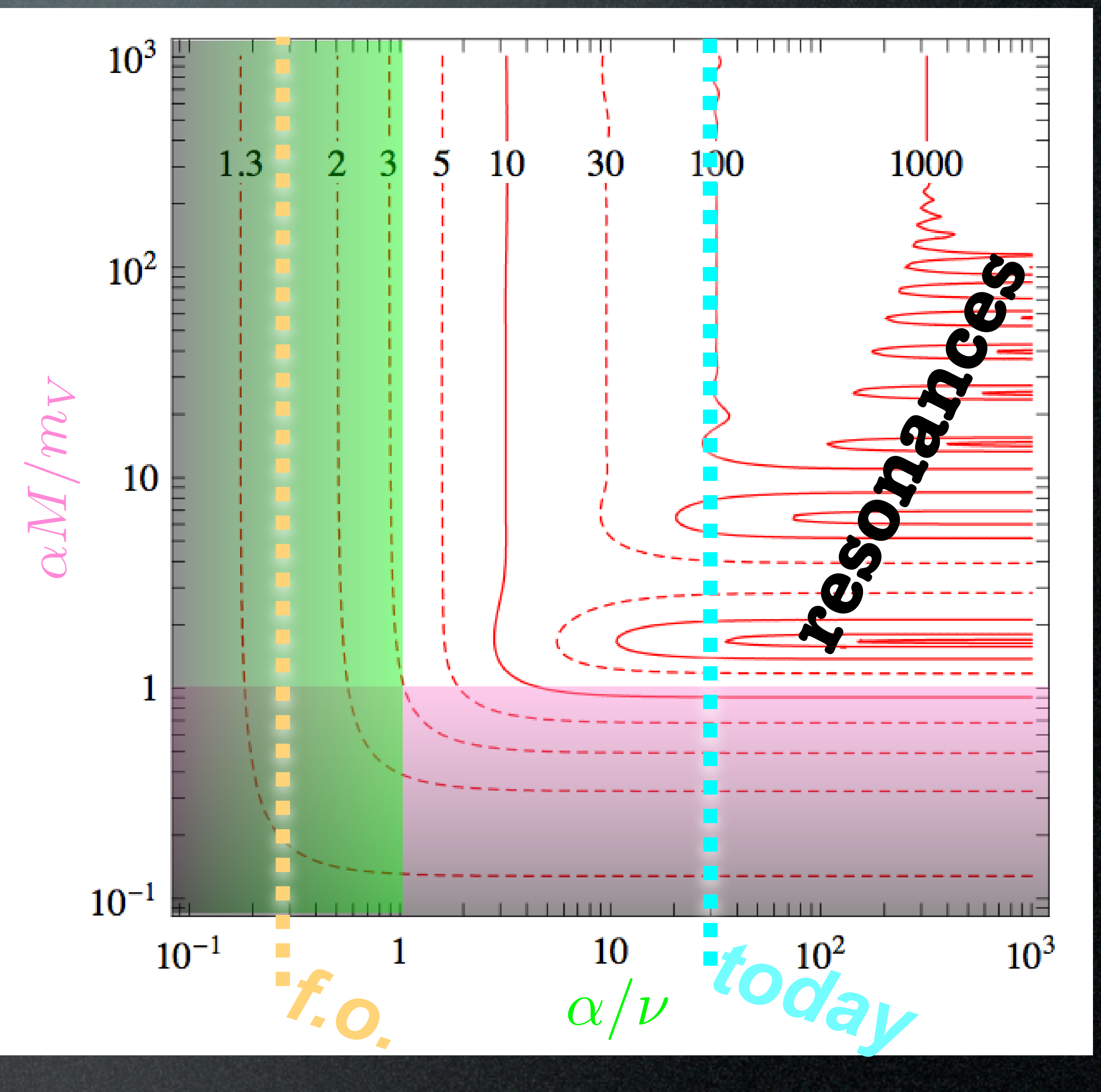

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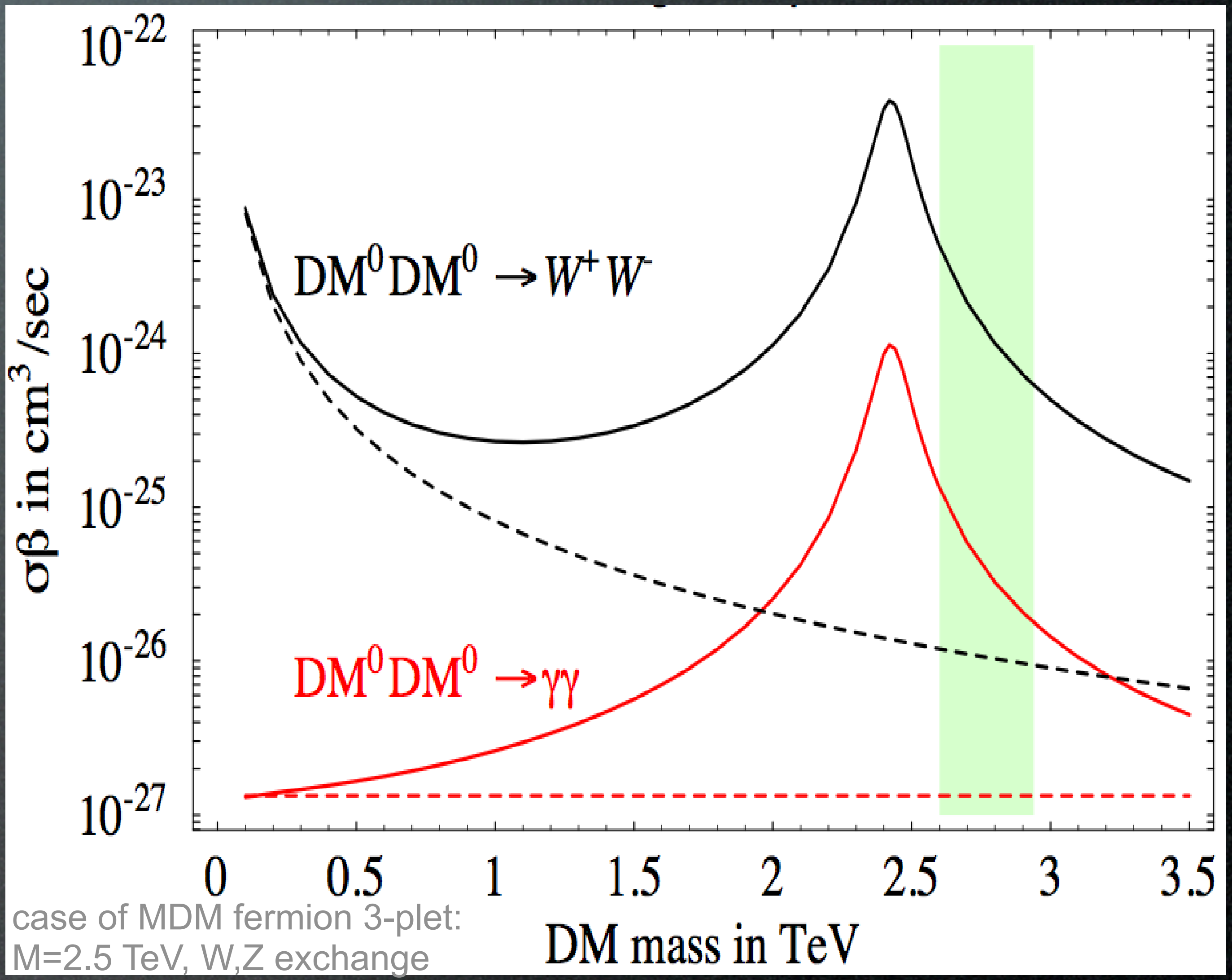

Sommerfeld Enhancement

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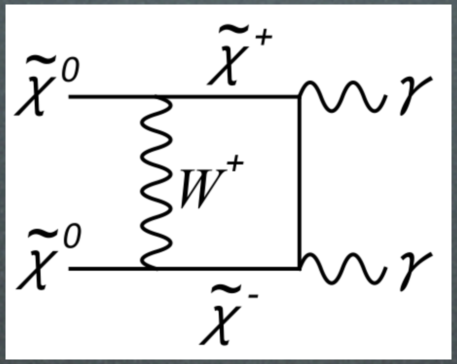
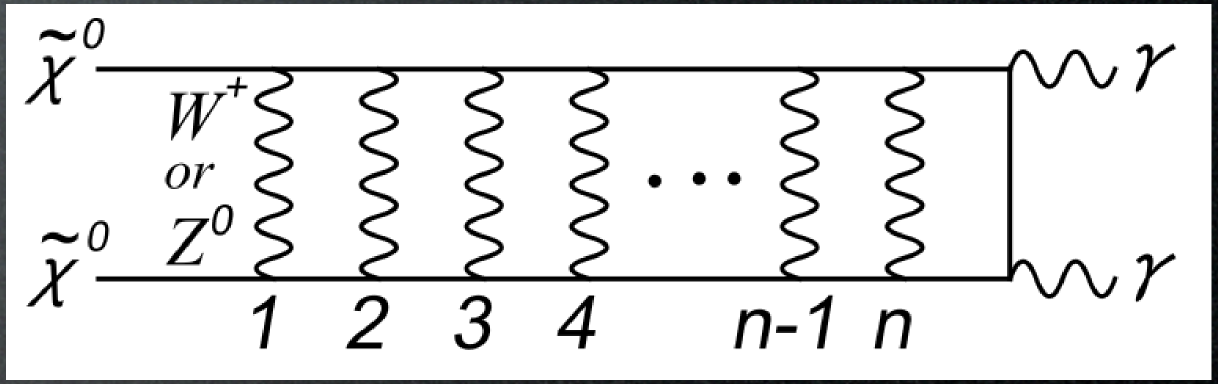
In terms of Feynman diagrams:

Hisano et al. hep-ph/0412403

First order cross section:



Adding a rung to the ladder: $\times \left(\frac{\alpha M}{m_W} \right)$



For $\alpha M / m_V \gtrsim 1$ the perturbative expansion breaks down,
need to resum all orders
i.e.: keep the full interaction potential.

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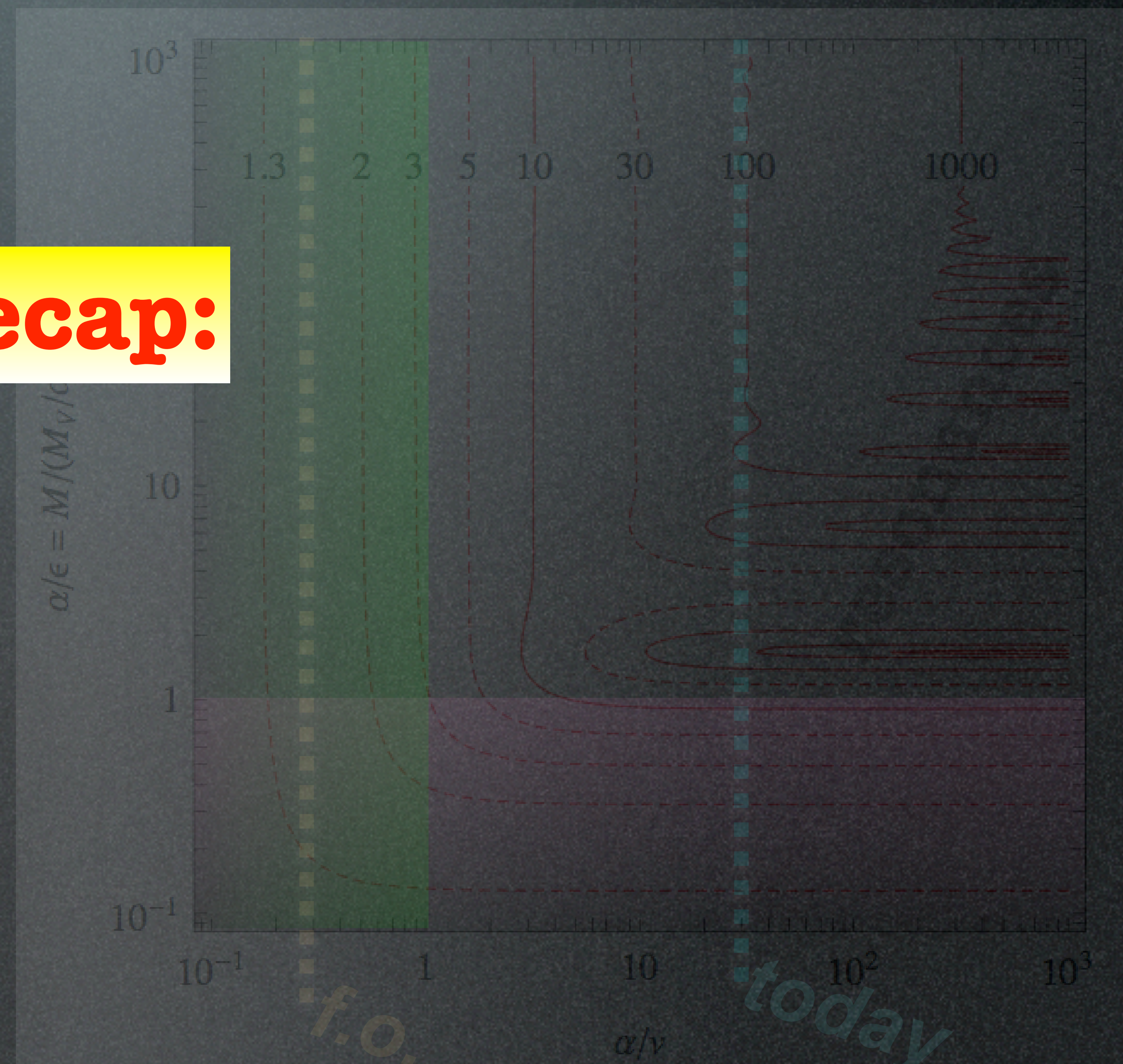

Recap:

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‘Conclusions’

Non-standard DM is non-dead and non-standing-still

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Non-standard DM is alive and kicking *

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like any newborn,
it builds on the expertise
of giants,
i.e. ‘old’ SuSy DM.

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I picked 3 recent ideas:

1. Minimal DM: the simplest, so-far-overlooked WIMP possibility?
2. Asymmetric DM: a paradigm of a ‘new’ production mechanism?
3. Secluded DM: the harbinger of a rich dark sector?

but the list of new interesting directions is bottomless.